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IFAC-PapersOnLine 49-23 (2016) 265–272

Underwater vehicle guidance control design within the DexROV project: preliminary results

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Abstract: The paper addresses the guidance control design of the motion controller for an underwater Remotely Operated Vehicle (ROV) within an European Commission H2020 research project called DexROV. Given a kinematics model of an ROV possibly subject to an ocean current, the problem consists in designing a guidance control law able to realize, within a common and unified framework, several basic control loops denoted as "primitives". The problem is rather standard when considering such primitives individually, but it becomes more challenging when aiming at designing a single general solution able to realize several different primitives according on how the reference signal for the controller is assigned. Moreover, the proposed guidance loop is required to operate in the presence of delays. The proposed solution builds on standard techniques leading to a Proportional - Integral (PI) controller with an adaptive gain selection rule to cope with integrator wind-up phenomena due to vehicle velocity saturation. The designed solution is numerically tested and analysed through simulations accounting for simplified, yet realistic, sensor models including stochastic noise and delays.

Keywords: marine systems, ROV, guidance, communication latencies.

1. INTRODUCTION

DexROV: Dexterous Undersea Inspection and Maintenance in Presence of Communication Latencies is an ongoing european research projects funded by the European Commission (EC) under the H2020 Research and Innovation programme. DexROV aims at the development of new underwater service capabilities with a focus on far distance teleoperation of Remotely Operated Vehicles (ROVs) involving variable communication latencies. In particular, the ROV pilot console within the DexROV project will be in a separate physical location (Onshore Control Center, OCC) with respect to the surface end of the ROV tether where guidance commands will be elaborated (Offshore Operations). The OCC will communicate with the ROV system through a satellite link exhibiting possibly non negligible delays. Moreover, the project vehicle will be equipped with a pair of manipulators. Indeed a second focus of the project is on advanced dexterous manipulation capabilities benefiting from context specific human skills and know-how also over long distances Gancet et al. (2015). The project is 3.5 years long and has started in March 2015.

This paper addresses the design of the guidance control system for the DexROV vehicle to be integrated with its navigation and actuator control systems as well as with the manipulator controller. Indeed the higher level specifications for the ROV guidance system are rather standard, yet the requirements related to a near-future integration with a specific manipulator control system and an ad-hoc navigation system suggest to aim at designing a *generic* guidance solution able to implement, within the very same kinematics control law, several different basic motion control loops. These will be called DexROV vehicle *primitives* in the following and include:

1. Hovering (dynamic positioning);
2. Autodepth;
3. Autoheading;
4. Autoaltitude;
5. Guidance to a target position.

The original contribution of the paper is related to the design of a single kinematics control solution able to seemingly implement all the requested primitives within a unique and general framework. Notice that from a technological point of view, the basic motion control functionalities associated with the listed primitives are rather standard as accounted for, by example, in Christ and Wernli (2014) and Fossen (2011). Indeed, starting from the pioneering work of Yoerger et al. (1986), many advanced motion control solutions for ROVs have been designed and tested in the last 30 years. Although the performance of such solutions will depend on the available specific actuation system (lower level control layer) and navigation system, at a guidance level (kinematics control layer) the motion control primitives can be designed independently of these sub-systems. Indeed, the preliminary results described in this paper refer to a solution based on a purely kinematics model of the ROV. As a result, the controller is a Proportional - Integral (PI) closed loop law. For the sake of brevity, the DexROV navigation system will not be described in detail. As illustrated in the following, only

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10.1016/j.ifacol.2016.10.353

some basic assumptions on the available feedback will be made and their impact on the proposed guidance laws will be discussed. Figure 1 shows a schematic representation of the DexROV control architecture. Essentially, the necessary feedback needed to close the loop is related to the estimated position and velocity of the vehicle as usually needed in Dynamic Positioning (DP) applications Sørensen (2011), Sørensen et al. (2012), Sørensen (2014). The proposed kinematics solution is numerically simulated including a simplified, yet realistic, model of Ultra Short Base Line (USBL) positioning system having a relatively low sampling frequency and a delay that is range dependent. Indeed, given such range dependent delay, the described simulation analysis suggests that the kinematics control can benefit from using adaptive gains as also discussed in the literature (Hoang and Kreuzer (2007)) for dynamic model based controllers of ROVs.

After describing the adopted notation and the guidance design methodology in sections 2 and 3 the motion primitive results are illustrated in section 4. Finally numerical results and conclusions are addressed in sections 5 and 6 respectively.

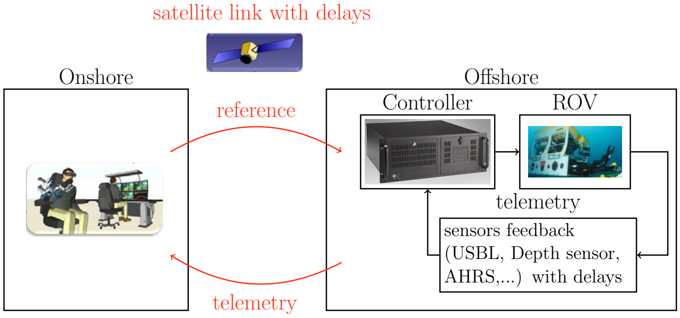

Fig. 1. DexROV Control Architecture.

2. NOTATION

The notation adopted in this paper is rather standard. For the sake of clarity and completeness we report the most significant notation details.

Vectors will be denoted in bold face fonts while matrices will be denoted by capital regular (not bold) fonts. Rotation matrices (i.e. elements of the special orthogonal group $SO(n)$ with n being 3 unless otherwise stated) will be indicated as ${}^1R_0$ being 0 and 1 the labels of the input and output frames respectively. Namely indicating with ${}^0\mathbf{b}$ the projection of vector $\mathbf{b}$ in frame 0, its components in frame 1 will be given by ${}^1\mathbf{b} = {}^1R_0\,{}^0\mathbf{b}$. Consequently, denoting with $\mathbf{i}_0, \mathbf{j}_0$ and $\mathbf{k}_0$ the unit vectors of frame 0, the rotation matrix ${}^1R_0$ results in:

$$ {}^1R_0 = \begin{bmatrix} {}^1\mathbf{i}_0 & {}^1\mathbf{j}_0 & {}^1\mathbf{k}_0 \end{bmatrix} $$

where ${}^1\mathbf{i}_0$, ${}^1\mathbf{j}_0$ and ${}^1\mathbf{k}_0$ are the projections of $\mathbf{i}_0, \mathbf{j}_0$ and $\mathbf{k}_0$ in frame 1.

The cross product $\mathbf{a} = \mathbf{b} \times \mathbf{c}$ among elements in $\mathbb{R}^3$ expressed as components with respect to a given frame can be computed as a matrix times vector operation in the form:

$$ \mathbf{a} = \mathbf{b} \times \mathbf{c} = S(\mathbf{b})\,\mathbf{c} $$

being the skew symmetric matrix $S(\cdot)$ given by:

$$ S(\mathbf{b}) = \begin{pmatrix} 0 & -b_3 & b_2 \\ b_3 & 0 & -b_1 \\ -b_2 & b_1 & 0 \end{pmatrix}. \tag{1} $$

3. KINEMATIC GUIDANCE DESIGN

3.1 Modelling

Let us consider the following kinematic model for the ROV:

$$ \dot{\mathbf{p}} = \mathbf{u} + \mathbf{v}_c \tag{2} $$

$$ {}^1\dot{R}_0 = -S({}^1\boldsymbol{\omega}_{1/0})\,{}^1R_0. \tag{3} $$

The linear velocity control input is the velocity with respect to the fluid $\mathbf{u} \in \mathbb{R}^3$, namely the linear motion model is fully actuated and eventually subject to a (matched) disturbance $\mathbf{v}_c$ representing the ocean current. The rotation matrix ${}^1R_0$ maps vectors from frame 0 to frame 1: in particular frame 0 is assumed to be an earth fixed frame (typically a North East Down - NED frame) and frame 1 is a body fixed frame having its x, y, z axis aligned to surge, sway and heave directions of the ROV. In the following, unless otherwise stated, equation (2) will be thought as expressed in frame 1. $\dot{\mathbf{p}}$ is the ROV velocity as projected in body frame. The rotational control input is ${}^1\boldsymbol{\omega}_{1/0}$ that represents the angular velocity of frame 1 with respect to 0 projected in frame 1.

Actually, the rotational motion model of the ROV used in DexROV, i.e. the APACHE 2500 in Figure 2, is not fully actuated, since the only actuated rotation is the yaw rotation. Moreover, the motion control scenario, within the DexROV project, is tipically a *setpoint regulation* where the desired position and attitude is a constant input or a setpoint provided by a human operator. Hence, the proposed guidance and control system consists of a linear velocity controller in combination with an heading controller.

3.2 Linear velocity control

Assuming the desired position to be $\mathbf{p}_d$ having velocity $\dot{\mathbf{p}}_d$, the position error would be:

$$ \mathbf{e} = \mathbf{p}_d - \mathbf{p} = (e_u, e_v, e_w)^\top. \tag{4} $$

Its time evolution (in body frame) is:

$$ \dot{\mathbf{e}} = \dot{\mathbf{p}}_d - \mathbf{u} - \mathbf{v}_c \tag{5} $$

suggesting for the control input $\mathbf{u}$ a PI with feedforward structure:

$$ \mathbf{u} = K_p\,\mathbf{e} + K_I \int_{t_i}^{t} \mathbf{e}(\tau)d\tau + \hat{\dot{\mathbf{p}}}_d - \hat{\mathbf{v}}_c \tag{6} $$

where $\hat{\dot{\mathbf{p}}}_d$ and $\hat{\mathbf{v}}_c$ are estimates of the desired velocity and ocean current. Assume:

$$ \hat{\dot{\mathbf{p}}}_d - \dot{\mathbf{p}}_d = \boldsymbol{\delta}_1 \quad : \quad \dot{\boldsymbol{\delta}}_1 = \mathbf{0} \tag{7} $$

$$ \hat{\mathbf{v}}_c - \mathbf{v}_c = \boldsymbol{\delta}_2 \quad : \quad \dot{\boldsymbol{\delta}}_2 = \mathbf{0} \tag{8} $$

that can be satisfied, by example, if $\dot{\mathbf{p}}_d$ and $\mathbf{v}_c$ are constant and their estimates are null. If assumption (7 - 8) hold, the closed loop error would evolve as: