Vehicle adaptive control for underwater intervention including thrusters dynamics

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Abstract—This paper investigates the effects of including the thruster dynamics within the full-dimensional adaptive control of an underwater vehicle. In particular, the intervention case, i.e., small movements around a steady reference trajectory and the presence of the ocean current, are of interest. The thruster dynamics influences the closed loop causing undesirable effects if not properly taken into account. Furthermore, as known, the adaptive control can fail if the performed trajectory is not sufficiently exciting causing eventually the dynamic parameters drift and bursting phenomena. Therefore, for the intervention case, these drawbacks of the adaptive control have to be considered. In particular, a reduced version of the controller, taking into account only the persistent dynamic effects, is implemented. Finally, numerical simulations validate the discussion made.

I. INTRODUCTION

The use of Autonomous Underwater Vehicles (AUVs) is crucial in underwater missions for a number of reasons, first of all the man’s safety. Within the DexROV [1] and ROBUST Horizon 2020 projects, the intervention cases in oil&gas and mining scenario are of interest (see Fig. 1 for the two renderings).

![DexROV and ROBUST renderings](image)

Fig. 1: DexROV (on the left) and ROBUST (on the right) rendering models.

Hovering control of vehicles is made difficult mainly by the uncertainty in the model parameters knowledge and by the low bandwidth and noisy sensors’ readings. Furthermore, high-performance actuator systems are required for station-keeping tasks. The actuator system is the lowest control level of the AUV. Differently from, e.g., industrial robotics, its dynamic effect is not straightforward and it is not efficient to neglect it during control design. Moreover, external disturbances such as the ocean current, both in module and direction, affect its dynamics. For an AUV the most common propulsion system is represented by thrusters. They are essentially divided into two subgroups: thrusters and tunnel thrusters. The latter are statically and dynamically more efficient [2], thus they are mainly used for manoeuvring operations. On the other hand, the standard propellers are optimized to produce thrust only in one direction and then they are utilized mostly for survey missions.

Different thruster models have been proposed in literature [3], [4], [5], [6]. The model is made complex by different hydrodynamic factors [7]. An one-state model was proposed by [3] where a lumped parameter dynamic model was developed. For a better description of the transient, a three-states one was introduced by [5] taking into account the axial flow velocity, sinusoidal lift-drag functions and the vehicle dynamics. However the axial flow velocity requires the use of an estimator to be known, increasing the complexity of the system. The work [6] proposed the axial flow as a linear combination of the thruster propeller speed and the ambient flow, validating it through different tests.

The thrusters represent thus an additional dynamics to be taken into account. However, its inclusion in the control scheme is made difficult in most of the off-the-shelf propellers by the lack of any sensor to read the necessary feedback, e.g., the thrust and propeller speed rotation. Furthermore the thruster performances are affected by other factors such as cross-flows and ocean current causing a thrust degradation [8]. Obviously, the latter directly depend on the thruster allocation [9], [10], [8]. Very recent studies [11] have shown that also delays due to the hardware can increase the degradation of the produced thrust if not properly taken into consideration.

The use of the adaptive control allows to adjust online the control gains solving the issues linked to the large uncertainty in the knowledge of model parameters. However when trajectories are not sufficiently exciting, such as the intervention case, the bursting phenomenon can happen [12]. In particular, this phenomenon is due to the lack of persistence of excitation condition [13]. Then some parameters are not identifiable any more and drifts until they act themselves as disturbance by injecting a wrong model compensation. Therefore the bursting needs to be properly taken into account to avoid possible system oscillations or even instability during intervention operations. A procedure to determine which parameters are identifiable [14] may represent a good method for managing the phenomenon described above.

In this work, extending [15] and using the dynamic model of the MARIS vehicle [16] and referring to the intervention case, an adaptive control law is investigated and then numerically studied including the thruster dynamics. In particular the steady state is of interest. Thus, taking into account the considerations made in [17], a reduced version of the controller is implemented and used in the numerical simulations.
II. MODELING

A. Vehicle's Kinematics

According to the nomenclature defined in [18], with respect to an earth-fixed inertial reference frame \( \Sigma_{r} \), the vehicle pose (position and orientation), described in function of a vehicle-fixed frame, can be expressed as \( \eta_{1} = [x \ y \ z]^{T} \in \mathbb{R}^{3} \) and \( R_{B}^{I} \in \mathbb{R}^{3 \times 3} \), respectively, where the latter matrix represents the transformation from vehicle-fixed frame to the inertial one. However, in marine applications, the vehicle orientation is commonly expressed in terms of the roll-pitch-yaw Euler angles \( \eta_{2} = [\psi \ \theta \ \psi]^{T} \in \mathbb{R}^{3} \). Thus the vehicle’s pose with respect to the inertial frame is \( \eta = [\eta_{1}^{T} \ \eta_{2}^{T}]^{T} \) and its time derivative is \( \dot{\eta} = [\eta_{1}^{T} \ \eta_{2}^{T}]^{T} \).

The velocity in vehicle-fixed frame is defined as \( \nu = [\nu_{1}^{T} \ \nu_{2}^{T}]^{T} \) where \( \nu_{1} = [u \ v \ w]^{T} \in \mathbb{R}^{3} \) is the vector of linear components and \( \nu_{2} = [p \ q \ r]^{T} \in \mathbb{R}^{3} \) is the vector of angular components.

At differential level, the relationship among velocities is defined as

\[
\dot{\eta} = \begin{bmatrix} R_{B}^{I} & O_{3 \times 3} \\ O_{3 \times 3} & T(R_{B}^{I}) \end{bmatrix} \begin{bmatrix} \nu_{1} \ \\ \nu_{2} \end{bmatrix} = J_{k}^{B} \begin{bmatrix} \nu_{1} \ \\ \nu_{2} \end{bmatrix},
\]

where \( O_{3 \times 3} \) is the null matrix and \( T \) is a transformation matrix expressed in function of Euler angles as defined in [19].

B. Vehicle’s Dynamics

Taking into consideration the intervention case with the possible presence of the ocean current, let us define the relative velocity in vehicle-fixed frame as

\[
\nu_{r} = \nu - \begin{bmatrix} R_{B}^{I} & O_{3 \times 3} \\ O_{3 \times 3} & O_{3 \times 3} \end{bmatrix} \nu^{I} \in \mathbb{R}^{6},
\]

where \( \nu^{I} \in \mathbb{R}^{6} \) is the ocean current velocity in \( \Sigma_{I} \). Then, the vehicle dynamics in body-fixed frame can be written as [20]:

\[
M \dot{\nu} + C_{RB}(\nu)\nu + C_{A}(\nu_{r})\nu_{r} + D(\nu_{r})\nu_{r} + g(R_{B}^{I}) = \tau_{v},
\]

where \( M = M_{RB} + M_{A} \in \mathbb{R}^{6 \times 6} \) is the inertia matrix given by the sum of the vehicle inertia and the added mass effects, \( C_{RB}(\nu) \), \( C_{A}(\nu_{r}) \in \mathbb{R}^{6 \times 6} \) are the centripetal and Coriolis terms relative to the vehicle and added mass effects, \( D(\nu_{r}) = D + D_{n}(\nu_{r}) \in \mathbb{R}^{6 \times 6} \) is the damping matrix given by the sum of linear and quadratic terms, respectively, \( g(R_{B}^{I}) \in \mathbb{R}^{6} \) is the vector of gravitational and buoyant generalized forces and \( \tau_{v} \in \mathbb{R}^{6} \) is the vector of forces and moments acting on the AUV. The dynamic model in Eq. (3) can be written in regressor form through the property of linearity in the parameters [19]:

\[
Y(R_{B}^{I}, \nu_{r}, \nu_{r}, \nu)\theta = \tau_{v},
\]

where \( \theta \in \mathbb{R}^{n} \) is the vector of dynamic model parameters.

It is worth noticing that in Eq. (3)-(4) the relative velocity \( \nu_{r} \) is introduced to put in evidence the dependence on the ocean current velocity \( \nu_{c} \). However, the latter does not represent a state variable but a constant parameter.

C. Thruster’s Dynamics

A generic tunnel thruster can be characterized by the following physical quantities [15]: the axial flow velocity into the propeller \( \upsilon_{p} \), the thruster motor torque \( \tau_{m} \), the rotation shaft speed \( n \) and the produced axial thrust \( T \). Furthermore, most of propellers are electrically driven. Thus, they present a DC-motor which receives a voltage control input \( \upsilon_{m} \).

However, accurate thruster modelling is quite complex since there are several hydrodynamic factors that need to be taken into consideration and in real systems the measuring of all necessary quantities is not always available. For these reasons, in literature several analysis studies have been made proposing different models. In particular, within the aim to focus the attention on the intervention case and therefore on the steady state, the model proposed by [3] has been selected.

In detail, in the latter work, using an energy-based method, the following lumped parameter model was proposed

\[
\dot{n} = -\alpha n|n| + \beta \upsilon_{m}, \quad T = C_{t} n|n|,
\]

where Eq. (5) represents the propellers dynamics with \( \alpha \) and \( \beta \) constant model parameters, and Eq. (7) is the mapping between the propeller thrust and the rotation speed, with \( C_{t} \) a proportional constant that is experimentally determined.

The above model is suitable for very low velocities. However, it does not take into account any interaction with the ambient flow and thus with the eventual ocean current \( \nu_{c} \).

Indeed, the thruster performances are differently affected by the ocean current depending on whether the vehicle is going against or in the same direction, (see Fig. 2). In particular,

\[
\begin{align*}
\psi < 0 & \quad \psi > 0
\end{align*}
\]

![Fig. 2: Two possible scenarios: thrusting in the same direction (negative yaw angle) or against (positive yaw angle) the ocean current.](image)

according to the considered scenarios, Eq. (7) is rewritten as

\[
T = C_{t} n|n|k_{1} \exp \left( k_{2}[0 \ 1 \ 0]^{T}(R_{th}^{B})^{T} \nu_{r} \right)
\]

where \( k_{1}, k_{2} \) are further terms depending on the relative velocity \( \nu_{r} \), \( [0 \ 1 \ 0] \) is a selection vector and \( R_{th}^{B} \) represents the thruster orientation with respect to the body-fixed frame [8]. Therefore, different effects on the produced thrust are obtained as shown in Fig. 3.
D. Force/moment-thruster mapping

The vector of forces and moments acting on the vehicle needs to be mapped into the thruster control inputs \( \mathbf{u}_{tr} \in \mathbb{R}^p \), with \( p \) the number of propellers. However, the mapping relation is not linear since it depends on the specific propeller features and several hydrodynamic factors. Indeed, the following mapping, that does not take into account the thruster dynamics, is commonly used:

\[
\mathbf{\tau}_v = \mathbf{B} \mathbf{u}_{tr} \in \mathbb{R}^6 ,
\]

(8)

where \( \mathbf{B} \in \mathbb{R}^{6 \times p} \) is a constant matrix depending on thruster allocation known as Thruster Configuration Matrix (TCM).

The latter relation, beyond the propeller dynamics, also represents the \( i \)-th thruster dynamics. More in detail, each term \( K_i \) is a function of the relative velocity \( \mathbf{v}_r \), necessary to take into account the ocean current effects, the vehicle orientation \( \mathbf{R}_B^B \) and the thruster orientation \( \mathbf{R}_{th}^B \) with respect to the body-fixed frame [15]. It is worth noticing that the thruster orientation \( \mathbf{R}_{th}^B \) does not represent a state variable. Hence, its presence in Eq. (10), as a functional dependence, is not analytically correct. However, this way results preferable to make the analysis more understandable to the reader.

III. CONTROLLER

Most of the controllers ignore the presence of the thrusters, and the corresponding dynamics, mainly due to the difficulty to feed back the relevant variables.

In the following, the adaptive controller presented in [17], [21] will be first discussed in terms of the excitability and then in terms of its dynamic behavior with the introduction of the thrusters dynamics.

Defining the vehicle desired pose as \( \mathbf{\eta}_d(t) \in \mathbb{R}^6 \) and the corresponding desired velocity as \( \mathbf{\nu}_d(t) \in \mathbb{R}^6 \), respectively, the following is introduced:

\[
\mathbf{\nu}_{\text{ref}} = \mathbf{\nu}_d + \begin{bmatrix} \lambda_p \mathbf{I}_{3 \times 3} & \mathbf{O}_{3 \times 3} \\ \mathbf{O}_{3 \times 3} & \lambda_m \mathbf{I}_{3 \times 3} \end{bmatrix} \mathbf{e}
\]

(11)

where \( \mathbf{e} \in \mathbb{R}^6 \) is the pose error, with the orientation expressed in unit quaternion, and \( \lambda_p, \lambda_m \) are positive gains. Furthermore, the following variable \( \mathbf{s} = \mathbf{\nu}_{\text{ref}} - \mathbf{\nu} \) is introduced. Thus, with reference to the Eq. (4) expressed in regressor-form, the control law is

\[
\mathbf{\tau}_e = \mathbf{Y} \dot{\theta} + \mathbf{K}_s \mathbf{s} ,
\]

(12)

where the vector of the estimated dynamic parameters \( \dot{\theta} \) is updated according to the following relation

\[
\dot{\theta} = \mathbf{K}_\theta^{-1} \mathbf{Y}^T \mathbf{s}
\]

(13)

with \( \mathbf{K}_s \in \mathbb{R}^{6 \times 6} \) and \( \mathbf{K}_\theta \in \mathbb{R}^{\mu \times \mu} \) positive definite design matrices.

A. Reduced version

A reduced version, taking into account only the persistent dynamic terms, i.e., the terms affecting the hovering, has been proposed [21]. This version of the controller exhibits the minimum number of dynamic parameters yet guaranteeing null steady state error. In detail, the reduced regressor for a rigid body in a fluid is

\[
\mathbf{Y} = \begin{bmatrix} \mathbf{O} & \mathbf{R}_B^B & \mathbf{O} \\ \mathbf{S}\left(\mathbf{R}_B^T \mathbf{z}\right) & \mathbf{O} & \mathbf{R}_B^B \end{bmatrix}
\]

(14)

with \( \mathbf{z} = [0 \ 0 \ 1]^T \), where the first three-columns set represents the regressor elements related to the gravity/buoyancy moments whereas the second and third class are the ones related to the external force and moment disturbances, respectively.

As known in adaptive control theory for robots [22], it is appropriate to further investigate the identifiability of the parameters. By SVD (Singular Value Decomposition) analysis of the regressor it has been observed that changes in roll and pitch are sufficient to excite all the parameters. On the other hand, if the vehicle is completely still, linear combinations can arise causing issues of identifiability of the related parameters. In practice small movements of the vehicle in hover are difficult to detect as singular case and they may cause numerical issues that can be solved resorting to the following further reduced regressor

\[
\mathbf{Y} = \begin{bmatrix} \mathbf{O} & \mathbf{R}_B^B \\ \mathbf{S}\left(\mathbf{R}_B^T \mathbf{z}\right) & \mathbf{O} \end{bmatrix}
\]

(15)

However, the latter does not ensure to compensate for the external moment disturbances. For these reasons, the first reduced regressor in Eq. (14) is used taking into account the possible phenomena of bursting [12]. Indeed, the presence of issues of identifiability joint to the presence of sensor noisy measurements, as usual in practice, may cause the system to burst into an oscillation which then dies away. More in
detail, the parameters not-identifiable drift according to a random walk dynamics (see Fig. 4 for a numerical example), a small movement of the vehicle may excite the parameter under discussion and inject the model-based compensation of the drifted parameter in the control loop as a disturbance. Depending on the amplitude of the drift, and thus the amplitude of the disturbance, the feedback may recover it by oscillating around the desired value while correctly estimating the parameters, or it can become unstable.

The overall effect of the bursting is difficult to predict for a generic mechanical system and depends by several factors among which: the inertia, the sensor noise, the duration of the non-exciting movement, etc.

**B. Thruster Dynamics inclusion**

The controllers are usually designed neglecting the thruster dynamics. However, since the thruster input is usually the voltage, the designer needs to estimate the thruster gain at steady state as shown in Fig. 5. Let us define as $\hat{K}_\infty \in \mathbb{R}^{p \times p}$, the diagonal matrix collecting those gains. Merging Eq. (9) and the controller in Eq. (12), the designer assumes the following relationship:

$$ B\hat{K}_\infty \hat{v}_m = \tau_c. \quad (16) $$

$$ v_m = \hat{K}_\infty^{-1} B^T \tau_c. \quad (17) $$

However, since $\hat{K}_\infty$ is only an approximation of $K$ the real input to the dynamic system is

$$ \tau_v = B\hat{K}_\infty^{-1} B^T \tau_c \quad (18) $$

where, as discussed earlier

$$ K = K(\nu_r, R_i^B, R_i^B) , \quad (19) $$

i.e., each thruster reacts in a different manner depending on its location on the vehicle with respect to the presence of the ocean current and the eventual error in the steady state estimate. It is interesting to discuss the effect on the rigid body dynamics.

The mapping of the control action $\tau_c$ to the physical wrench acting on the vehicle $\tau_v$ is distorted by the $(6 \times 6)$ matrix:

$$ K_{eq}(\nu_r, R_i^B, R_i^B) = B\hat{K}_\infty^{-1} B^T \quad (20) $$

which is assumed to be Identity by the designer while it is, on the contrary, constant at steady state and not even diagonal and couples the control directions.

With the risk to be redundant let us recopy eq. (12) merged with the relations above:

$$ \tau_v = K_{eq} Y \theta + K_{eq} K_s s \quad (21) $$

which clearly shows two distortion effects, first on the identified parameters and then on the control gains. The latter has potentially a dramatic effect, i.e., that the effective control gains are different from the ones tuned by trial-and-error in the pool due to the different working conditions.

**IV. NUMERICAL SIMULATIONS**

An open frame vehicle is considered for the case study whose dynamic parameters have been identified in [23]. The actuators, however, have been changed according to the thruster configuration shown in Fig. 6. In particular, it is a possible propeller allocation for a fully actuated and redundant vehicle for which the TCM is defined as

$$ v_m = \hat{K}_\infty^{-1} B^T \tau_c. \quad (17) $$

$$ K = K(\nu_r, R_i^B, R_i^B) . \quad (19) $$

An intervention operation and thus a station-keeping task is considered as case study. In particular, the vehicle is required to perform a small movement, with a trapezoidal velocity profile, along the $x$-direction maintaining the own
orientation. The simulations are performed with a sampling time $T = 10\,\text{ms}$ and measurement noise is not taken into account since the aim it to show the distortion introduced by $K_{eq}$. More in detail, the case study is simulated in three different conditions: the ideal condition where the thruster dynamics is neglected, the real one where the propeller dynamics with thruster degradation is considered and the latter with the presence of the ocean current which increases the thrust degradation. Indeed, in the most of cases the gain tuning phase is performed in a water tank, therefore with no ocean current, and, as mentioned above, neglecting the actuator dynamics due to the lack of sensors. Then, the resulting values are also used offshore. However, the controller performance deterioration has to be taken into account since the different operative conditions and the presence of propellers change the plant used to design the controller resulting in a $K_{eq}$ different from the identity matrix.

Figures 7 and 8 show the pose error and vehicle force norm, respectively. In particular, it is noticeable how the error increases from the Ideal condition to the Real one with the presence of the ocean current. However, the controller results stable with null steady state error.

**Fig. 7:** Position and orientation error norm plots: in blue the Ideal condition (no thruster dynamics); in red the Real condition (with thruster dynamics); in yellow the Real one with the presence of the ocean current.

**Fig. 8:** Vehicle force and moment norm plots: in blue the Ideal condition (no thruster dynamics); in red the Real condition (with thruster dynamics); in yellow the Real one with the presence of the ocean current.

Figure 9 represents the dynamic parameters corresponding to the linear components of the external force disturbances. In detail, it is observable that the presence of the ocean current $\nu_c = [2.2 0 0 0 0]^T$ influences the $x, y$ components differently from the other two conditions. Furthermore, the thruster dynamics included in $K_{eq}$ makes a clear distortion on the gravity-buoyancy component ($z$-component) which looses in this way its physical significance. To better understand, the $K_{eq}$, corresponding to the last sample of the Real condition simulations in presence of the ocean current,

$$
\begin{bmatrix}
.4756 & -0.0068 & 0 & 0 & 0 & 0.0269 \\
-0.0068 & .4756 & 0 & 0 & 0 & -0.0269 \\
0 & 0 & .5015 & 0 & 0 & 0 \\
0 & 0 & 0 & .5015 & 0 & 0 \\
0 & 0 & 0 & 0 & .5015 & 0 \\
0.0067 & -0.0067 & 0 & 0 & 0 & .4756 \\
\end{bmatrix}
$$

From these values it is clear that, differently from the Ideal case where $K_{eq}$ corresponds to the Identity matrix, in the Real condition the diagonal elements (in blue) can vary according to the specific system and movement and furthermore there may be out-diagonal elements (in red).
corresponding to direction couplings that increase with the ocean current. To further underline the effects of the $K_{eq}$ matrix, Fig. 10 shows a comparison between the external force disturbances obtained from the previous simulation (case (a)) and the ones obtaining with a 50% overestimation of $K_\infty$ (case (b)). Thus, on equal terms, the gain estimate also has a non-negligible effect.

Another consideration finally comes out from numerical simulations. In particular, the $K_{eq}$ matrix presents some off-diagonal elements that are always null. This means that some control directions can not be coupled by construction and they depend on the specific TCM. In this work, given the chosen thruster allocation, the following results:

$$K_{eq} = \begin{bmatrix} * & * & 0 & 0 & 0 & * \\ * & 0 & 0 & 0 & 0 & * \\ 0 & * & * & * & 0 & 0 \\ 0 & 0 & * & * & 0 & 0 \\ * & 0 & 0 & 0 & 0 & * \end{bmatrix}, \quad (22)$$

where the * symbol represents the generic diagonal element which varies around the value 1 and the generic out-diagonal element that varies around the value 0.

V. CONCLUSIONS

In this work the full-dimensional adaptive control of an underwater vehicle, including the thruster dynamics and the ocean current effects, has been investigated. In particular, the performed analysis has shown that these effects cause the vehicle control input $\tau_\nu$ distortion and they make the dynamics parameters loose their physical meaning.

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