A DIRECT ADAPTIVE CONTROL SYSTEM FOR MASS-VARYING UNDERWATER VEHICLES WITH MANIPULATOR

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Abstract: In this work, the design of an adaptive control algorithm for a general class of underwater vehicles with manipulator in the context of a path-following problem is presented. The algorithm is based on speed-gradient techniques and state/disturbance observer. A stepwise changing mass is assumed during the operations of the vehicle manipulator. The influence of the unknown mass on the control performance is indirectly captured by means of adaptive tracking control. A case study illustrates the features of our approach by means of numerical simulations.

Keywords: Adaptive nonlinear control, Tracking control, Autonomous vehicles, Time-variyng systems, Nonlinear systems.

1. INTRODUCTION

One of the most critical tasks in the teleoperation of manipulator arms attached on subaquatic vehicles, is the stabilization of the vehicle on part of the operator during operations at underwater constructions or on the sea bottom. Sometimes, the demanded precision is of an order of magnitude within a few centimeters. Such scenarios are very common in operations of welding, assembling, drilling, sampling, among others (see Fossen, 1995).

The distribution of mass about the main vehicle axes plays an important role by control systems of ROVs (remotely operated vehicles) in both respects, on one side, achieving desired dynamic positioning, and on the other side, counteracting reactive forces through the teleoperation of the arm. Thus, bounds for inertia must be taken into account in the controller design to confer the teleoperation wide margins of comfortability and vehicle maneuverability, but in extreme cases, also helping to preserve stability against capsizing.

Inertia properties can be determined *ad-hoc* in a commissioning phase before the control system be designed. This task is particularly important in oceanographic applications when the instrumentation needed for a research mission is basically diverse and constantly changeable in weight, shape and volume. Similarly, in more technical applications in the off-shore industry, the subaquatic transportation of elements of diverse masses, or, in research applications, the sampling of elements with unknown mass from the sea bottom, entail basically the same difficulty.

As most commercial underwater manipulators belong to master-slave type, they usually require the operator be well trained and fully skilled. When

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the previously mentioned scenarios occur, the operator will instinctively attempt to compensate performance drops by closing the control loop through the human interface during teleoperation, which can lead to undesired instability.

Therefore, it is desirable that a complementary automatic control loop can fit somehow new dynamics arriving from particular arrangement of instruments, or that it can make self-adjustments in the control behavior against mass changes or force perturbations in order to preserve stability and accomplish acceptable levels of performance. In this respect robust and/or adaptation abilities in the control system could be very useful to the operator, in order for him/her to only concentrate on reference path generation or arm manipulation.

Some techniques appear in the specific literature, ranging from sliding-mode-based control systems for sevomechanisms (Liu and Feng, 2005) and parameter identification for model-based control of variable-configuration vehicles (Caccia *et al.*, 2000). Also, adaptive and learning methods were developed in (Yuh, 1990; Fossen and Fjellstad, 1995; Ishii *et al.*, 1995; Cristi *et al.*, 1990; Venugopal *et al.*, 1992; Leonard, 1995; Smallwood and Whitcomb, 2004), among others. Although all of them are concerned with the problem of uncertainties, in general, only a few ones tackle the problem of time-varying parameters specifically.

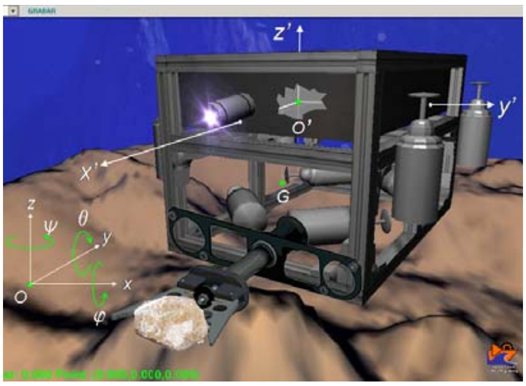

Fig. 1 - Port/starboard symmetric ROV with manipulator (case study)

In this paper, we present a novel approach to direct adaptive control for path following of underwater vehicles in 6 degrees of freedom with a manipulator arm. A similar adaptive method was presented in (Jordán and Bustamante, 2006), however it was required therein the *a-priori* knowledge of the mass-center coordinates and its constancy in time.

2. VEHICLE DYNAMICS

Let a body-fixed coordinate system be that illustrated in Fig. 1 for an origin O' coincident with the navigation sensor system. So, the center of gravity G has coordinates given by $\mathbf{r}_G = [x_G, y_G, z_G]^T$ with respect to O'. The system states are the vehicle position vector, referred to as $\boldsymbol{\eta}$, with respect to a ground-fixed coordinate system O, and the speed vector $\mathbf{v}$ with respect to the vehicle-fixed coordinate system O'. In details $\boldsymbol{\eta}= [x, y, z, \phi, \theta, \psi]^T$ includes translations along the main axes (*i.e.*, surge, sway and heave) and tilts about them (*i.e.*, pitch, roll and yaw), and $\mathbf{v}= [u, v, w, p, q, r]^T$ includes the respective linear speeds and rotation rates in the vehicle-fixed system.

The general 6-DOF rigid-body equations are (*cf.* Fossen, 1995)

$$M\dot{\mathbf{v}} = -C(\mathbf{v})\mathbf{v} - D(|\mathbf{v}|)\mathbf{v} + \mathbf{F}_b(\boldsymbol{\eta}) + \mathbf{F}_c + \mathbf{F}_t \quad (1)$$

$$\dot{\boldsymbol{\eta}} = J(\boldsymbol{\eta})\mathbf{v}, \quad (2)$$

where M is a non-diagonal inertia matrix and C a Coriolis matrix, both conceived as a sum of a rigid-body and an added mass components, as respectively indicated in

$$M(t) = M_b(t) + M_a(t) \quad (3)$$

$$C(\mathbf{v}) = C_b(\mathbf{v}) + C_a(\mathbf{v}), \quad (4)$$

D is a damping matrix with two components accounting for linear and quadratic skin friction due to laminar and turbulent boundary layers, respectively, it is

$$D(\mathbf{v}) = D_l + D_q(|\mathbf{v}|), \quad (5)$$

$\mathbf{F}_b$ is a restoring generalized force, $\mathbf{F}_c$ is a reactive force of the umbilical cable and finally $\mathbf{F}_t$ is the generalized thrust force. Finally, J is the well-known 6×6 dimensional rotation matrix (see Fossen, 1995). The notation $|\mathbf{v}|$ is applied for a vector with elements of $\mathbf{v}$ in absolute values.

More specifically, the system matrices take the general form

$$M_b = \begin{bmatrix} m & 0 & 0 & 0 & mz_G & -my_G \\ 0 & m & 0 & -mz_G & 0 & mx_G \\ 0 & 0 & m & my_G & -mx_G & 0 \\ 0 & -mz_G & my_G & I_x & -I_{xy} & -I_{xz} \\ mz_G & 0 & -mx_G & -I_{yx} & I_y & -I_{yz} \\ -my_G & mx_G & 0 & -I_{zx} & -I_{zy} & I_z \end{bmatrix} \quad (6)$$

$$M_a = \left(m_{a_{ij}}\right), \text{ for } i,j = 1,...,6 \quad (7)$$

$$C_b(\mathbf{v}) = \begin{bmatrix} 0 & 0 & 0 & m(y_Gq+z_Gr) & -m(x_Gq-w) & -m(x_Gr+v) \\ 0 & 0 & 0 & -m(y_Gp+w) & m(z_Gr+x_Gp) & -m(y_Gr-u) \\ 0 & 0 & 0 & -m(z_Gp-v) & -m(z_Gq+u) & m(x_Gp+y_Gq) \\ -m(y_Gq+z_Gr) & m(y_Gp+w) & m(z_Gp-v) & 0 & -I_{yz}q-I_{xz}p+I_zr & I_{yz}r+I_{xz}p-I_yq \\ m(x_Gq-w) & -m(z_Gr+x_Gp) & m(z_Gq+u) & I_{yz}q+I_{xz}p-I_zr & 0 & -I_{xz}r-I_{xy}q+I_xp \\ m(x_Gr+v) & m(y_Gr-u) & -m(x_Gp+y_Gq) & -I_{yz}r-I_{xy}p+I_yq & I_{xz}r+I_{xy}q-I_xp & 0 \end{bmatrix} \quad (8)$$

$$C_a(\mathbf{v}) = \begin{bmatrix} 0 & 0 & 0 & 0 & -c_{a_3} & c_{a_2} \\ 0 & 0 & 0 & c_{a_3} & 0 & -c_{a_1} \\ 0 & 0 & 0 & -c_{a_2} & c_{a_1} & 0 \\ 0 & -c_{a_3} & c_{a_2} & 0 & -c_{a_6} & c_{a_5} \\ c_{a_3} & 0 & -c_{a_1} & c_{a_6} & 0 & -c_{a_4} \\ -c_{a_2} & c_{a_1} & 0 & -c_{a_5} & c_{a_4} & 0 \end{bmatrix} \quad (9)$$

$$D_l = (d_{q_{ij}}), \text{ for } i,j = 1, ..., 6 \quad (10)$$

$$D_q(|\mathbf{v}|) = \begin{bmatrix} |\mathbf{v}|^T D_{q_1} \\ \cdots \\ |\mathbf{v}|^T D_{q_6} \end{bmatrix}, \quad (11)$$

where m is the total vehicle mass, $m_{a_{ij}}$ the additive mass elements in each cross modes ij, I_{ij} are elements in M_b representing inertia moments with respect to axes ij, (x_G, y_G, z_G) are the coordinates of the mass center, the functions c_{a_i} in C_a are $c_{a_i} = \sum_{j=1}^{6} m_{a_{ij}} v_j$ with v_j the element j of $\mathbf{v}$, and finally the D_{q_i}'s in D_q are 6×6 constant matrices. The metacenter and mass center lie both in the plane x'-z'. Thus, the buoyancy vector is expressed as

$$\mathbf{F}_b(\boldsymbol{\eta}) = \quad (12)$$

$$\begin{bmatrix} (W\text{-}W_w)\,\mathrm{s}(\theta) \\ -(W\text{-}W_w)\,\mathrm{c}(\theta)\,\mathrm{s}(\phi) \\ -(W\text{-}W_w)\cos(\theta)\cos(\phi) \\ -(Wy_G\text{-}W_w y_B)\,\mathrm{c}(\theta)\,\mathrm{c}(\phi) + (Wz_G\text{-}W_w z_B)\,\mathrm{c}(\theta)\,\mathrm{s}(\phi) \\ (Wx_G\text{-}W_w x_B)\,\mathrm{c}(\theta)\,\mathrm{c}(\phi) + (Wz_G\text{-}W_w z_B)\,\mathrm{s}(\theta) \\ -(Wy_G\text{-}W_w y_B)\,\mathrm{s}(\theta) - (Wx_G\text{-}W_w x_B)\,\mathrm{c}(\theta)\,\mathrm{s}(\phi) \end{bmatrix}$$

where (x_B, y_B, z_B) are the coordinates of the metacenter, W is the vehicle total weight mg, W_w is the buoyancy, and s(.) and c(.) are the sine and cosine functions, respectively.

The generalized thrust force $\mathbf{F}_t$ is computed by the controller for the system O'. This force can be decomposed into the thrust vector $\mathbf{f} = [f_1, f_2, ..., f_{n_f}]^T$ with n_f the number of thrusters. Both vectors are related by

$$\mathbf{f} = B^T \left(BB^T\right)^{-1} \mathbf{F}_t, \quad (13)$$

with the matrix B containing constructive vehicle constants. The thruster dynamics is

$$\mathbf{n} = \mathcal{C}^{-1}(\mathbf{f}) = \mathcal{C}^{-1}\left(B^T (BB^T)^{-1} \mathbf{F}_t\right) \quad (14)$$

$$\mathbf{n}_r = \left(1 - \frac{N(s)}{b_0}\right) \mathbf{n}_r + \frac{D(s)}{b_0} \mathbf{n} \quad (15)$$

$$\mathbf{f}_r = \mathcal{C}(\mathbf{n}_r), \quad (16)$$

where $\mathbf{n}$ and $\mathbf{n}_r$ are vectors with the true thruster rpm's and its reference, respectively, $\mathbf{f}_r$ is the reference for the thrust vector $\mathbf{f}$, $\mathcal{C}$ is a static, nonlinear, continuous and invertible propeller characteristic in vector form, and finally, $D(s)$ and $N(s)$ are Hurwitz polynomials in the Laplace variable s with $b_0 = N(0)$ (Jordán *et al.*, 2005).

3. THE ADAPTIVE CONTROL APPROACH

3.1 Path-tracking problem

We are involved with the control objective

$$\lim_{t \to \infty} \boldsymbol{\eta}(t) - \boldsymbol{\eta}_r(t) = \mathbf{0} \quad (17)$$

$$\lim_{t \to \infty} \mathbf{v}(t) - \mathbf{v}_r(t) = \mathbf{0}, \quad (18)$$

for arbitrary bounded initial conditions $\boldsymbol{\eta}(0)$ and $\mathbf{v}(0)$ and smooth positioning and cinematic references $\boldsymbol{\eta}_r(t)$ and $\mathbf{v}_r(t)$, respectively. To attain (17)-(18), a control action law is designed to conveniently manipulate the thrusts f_j in $\mathbf{f}$. The adaptive objective supposes additionally that (6)-(12) are unknown.

To this end, let us define (*cf*. Jordán and Bustamante, 2006)

$$\breve{\boldsymbol{\eta}} = \boldsymbol{\eta} - \boldsymbol{\eta}_r \quad (19)$$

$$\breve{\mathbf{v}} = \mathbf{v} - J^{-1}(\boldsymbol{\eta})\dot{\boldsymbol{\eta}}_r + J^{-1}(\boldsymbol{\eta}) K_p \breve{\boldsymbol{\eta}}, \quad (20)$$

with a gain matrix $K_p = K_p^T \geq 0$ and an energy cost functional

$$Q(\breve{\boldsymbol{\eta}}, \breve{\mathbf{v}}) = \frac{1}{2}\breve{\boldsymbol{\eta}}^T \breve{\boldsymbol{\eta}} + \frac{1}{2}\breve{\mathbf{v}}^T M \breve{\mathbf{v}}, \quad (21)$$

which must be a radially unbounded and nonnegative scalar function (Fradkov *et al.*, 1999).

For an asymptotic stable controlled dynamics in the state space $\left[\boldsymbol{\eta}^{\mathbf{T}}, \mathbf{v}^T\right]^T$, it is aimed that for every initial mismatches $\breve{\boldsymbol{\eta}}(0)$ and $\breve{\mathbf{v}}(0)$, one accomplishes

$$Q(\breve{\boldsymbol{\eta}}(t), \breve{\mathbf{v}}(t)) \to 0, \text{ for } t \to \infty. \quad (22)$$

According to the speed-gradient approach, the manipulated variable, in this case the generalized force $\mathbf{F}_t$, can be designed by considering certain properties of $\dot{Q}$ like smoothness, convexity and radially growth in some compact $\mathcal{D}$ in the state space. So, taking the first derivative of (21) with (19)-(20), one gets

$$\begin{aligned} \dot{Q}(\breve{\boldsymbol{\eta}}, \breve{\mathbf{v}}, \boldsymbol{\eta}, t) &= -\breve{\boldsymbol{\eta}}^T K_p \breve{\boldsymbol{\eta}} + \breve{\boldsymbol{\eta}}^T J(\boldsymbol{\eta})\breve{\mathbf{v}} - \quad (23) \\ &-\breve{\mathbf{v}}^T C(\mathbf{v})\,\mathbf{v} - \breve{\mathbf{v}}^T D_l \mathbf{v} - \breve{\mathbf{v}} D_q(|\mathbf{v}|)\,\mathbf{v} - \\ &-\breve{\mathbf{v}}^T \mathbf{F}_b(\boldsymbol{\eta}) + \breve{\mathbf{v}} \mathbf{F}_c - \breve{\mathbf{v}}^T M \frac{d}{dt}\left(J^{-1}(\boldsymbol{\eta})\dot{\boldsymbol{\eta}}_r\right) + \\ &+\breve{\mathbf{v}}^T M \left(\frac{dJ^{-1}(\boldsymbol{\eta})}{dt} K_p - J^{-1}(\boldsymbol{\eta}) K_p^2\right) \breve{\boldsymbol{\eta}} + \\ &+\breve{\mathbf{v}}^T M J^{-1}(\boldsymbol{\eta}) K_p J(\boldsymbol{\eta}) \breve{\mathbf{v}} + \breve{\mathbf{v}}^T \mathbf{F}_t \,. \end{aligned}$$

Thus, a suitable selection of $\mathbf{F}_t$ for the aimed properties of $\dot{Q}$ is (*cf*. Jordán and Bustamante, 2006)

$$\begin{aligned} \mathbf{F}_t &= \sum_{i=1}^{6} U_i. \times C_{0_i}(v_i)\mathbf{v} + U_7 \mathbf{v} + \quad (24) \\ &+ \sum_{j=8}^{13} U_j. \times D_{0_{j\text{-}7}}(|v_{j\text{-}7}|)\mathbf{v} + U_{14}\mathbf{F}_{b_1}(\boldsymbol{\eta}) + U_{15}\mathbf{F}_{b_2}(\boldsymbol{\eta}) + \\ &+ U_{16}\,\mathbf{d}\left(\boldsymbol{\eta}, \breve{\boldsymbol{\eta}}, \breve{\mathbf{v}}, t\right) - \mathbf{F}_c - K_v \breve{\mathbf{v}} - J^T(\boldsymbol{\eta})\breve{\boldsymbol{\eta}}, \end{aligned}$$

with

$$\begin{aligned} \mathbf{d}\left(\breve{\boldsymbol{\eta}}, \breve{\mathbf{v}}, \boldsymbol{\eta}, t\right) &= \frac{d}{dt}\left(J^{-1}(\boldsymbol{\eta})\dot{\boldsymbol{\eta}}_r\right) - \frac{dJ^{-1}(\boldsymbol{\eta})}{dt} K_p \breve{\boldsymbol{\eta}} + \\ &+ J^{-1}(\boldsymbol{\eta}) K_p^2 \breve{\boldsymbol{\eta}} - J^{-1}(\boldsymbol{\eta}) K_p J(\boldsymbol{\eta}) \breve{\mathbf{v}}, \quad (25) \end{aligned}$$

where U_i are controller matrices of unknown coefficients accounting for physical parameters that have to be found adaptively, C_{0_i} and D_{0_i} are velocity-dependent matrices explained later, $\mathbf{F}_{b_1}$ and $\mathbf{F}_{b_2}$ are tilt-dependent vectors also cleared next, and finally K_v is a matrix with $K_v = K_v^T \geq 0$. The notations ".×" means element-by-element matrix product. Moreover, it was assumed the case that $\mathbf{F}_c$ can be measured without error.

According to the general formulation of speed-gradient algorithm any allowable candidate $\mathbf{F}_t$ must be such a one that $\dot{Q}(U_i)$ result convex in every element $u_{k_{ij}}$ of the U_i's. It straightforward to verify from (23) with (24) that this condition is also satisfied.

3.2 Adaptive laws

Now, one can calculate the functions U_i's by means of adaptive control laws based on gradient functions as $\dot{U}_i = -\Gamma_i \frac{\partial \dot{Q}}{\partial U_i}$. The main idea consists in separating coefficients from variables in the dynamics equations.

Towards this goal, consider (24) and let first the Coriolis matrix C in (4) be expressed as $\sum_{i=1}^{6} C_i.\times C_{0i}(v_i)$ with C_i constant matrices. So, it is valid for U_i with $i = 1, ..., 6$ the laws

$$\dot{U}_i = -\Gamma_i \begin{bmatrix} 0 & 0 & 0 & 0 & \tilde{u}v_i q & \tilde{u}v_i r \\ 0 & 0 & 0 & \tilde{v}v_i p & 0 & \tilde{v}v_i r \\ 0 & 0 & 0 & \tilde{w}v_i p & \tilde{w}v_i q & 0 \\ 0 & \tilde{p}v_i v & \tilde{p}v_i w & 0 & \tilde{p}v_i q & \tilde{p}v_i r \\ \tilde{q}v_i u & 0 & \tilde{q}v_i w & \tilde{q}v_i p & 0 & \tilde{q}v_i r \\ \tilde{r}v_i u & \tilde{r}v_i v & 0 & \tilde{r}v_i p & \tilde{r}v_i q & 0 \end{bmatrix}, \quad (26)$$

where $\tilde{u}, ..., \tilde{r}$ are elements of $\check{\mathbf{v}}$. Next, for D_l there corresponds the law

$$\dot{U}_7 = -\Gamma_7 \begin{bmatrix} \tilde{u}u & \tilde{u}v & \tilde{u}w & \tilde{u}p & \tilde{u}q & \tilde{u}r \\ \tilde{v}u & \tilde{v}v & \tilde{v}w & \tilde{v}p & \tilde{v}q & \tilde{v}r \\ \tilde{w}u & \tilde{w}v & \tilde{w}w & \tilde{w}p & \tilde{w}q & \tilde{w}r \\ \tilde{p}u & \tilde{p}v & \tilde{p}w & \tilde{p}p & \tilde{p}q & \tilde{p}r \\ \tilde{q}u & \tilde{q}v & \tilde{q}w & \tilde{q}p & \tilde{q}q & \tilde{q}r \\ \tilde{r}u & \tilde{r}v & \tilde{r}w & \tilde{r}p & \tilde{r}q & \tilde{r}r \end{bmatrix}. \quad (27)$$

Analogously, D_q can be expressed as $\sum_{j=8}^{13} D_{q_j}.\times D_{0_{j-7}}(|v_{j-7}|)$ with D_{q_j} constant matrices, for which following laws there will be assigned

$$\dot{U}_j = -\Gamma_j \quad (28)$$
$$\begin{bmatrix} \tilde{u}|v_k|u & \tilde{u}|v_k|u & \tilde{u}|v_k|w & \tilde{u}|v_k|p & \tilde{u}|v_k|q & \tilde{u}|v_k|r \\ \tilde{v}|v_k|u & \tilde{v}|v_k|v & \tilde{v}|v_k|w & \tilde{v}|v_k|p & \tilde{v}|v_k|q & \tilde{v}|v_k|r \\ \tilde{w}|v_k|u & \tilde{w}|v_k|v & \tilde{w}|v_k|w & \tilde{w}|v_k|p & \tilde{w}|v_k|q & \tilde{w}|v_k|r \\ \tilde{p}|v_k|u & \tilde{p}|v_k|v & \tilde{p}|v_k|w & \tilde{p}|v_k|p & \tilde{p}|v_k|q & \tilde{p}|v_k|r \\ \tilde{q}|v_k|u & \tilde{q}|v_k|v & \tilde{q}|v_k|w & \tilde{q}|v_k|p & \tilde{q}|v_k|q & \tilde{q}|v_k|r \\ \tilde{r}|v_k|u & \tilde{r}|v_k|v & \tilde{r}|v_k|w & \tilde{r}|v_k|p & \tilde{r}|v_k|q & \tilde{r}|v_k|r \end{bmatrix}.$$

with $k = j - 7$. Next, the buoyancy vector $\mathbf{F}_b$ can be decomposed into two vector terms as $B_1\mathbf{F}_{b_1} + B_2\mathbf{F}_{b_2}$, for which there corresponds each one the laws

$$\dot{U}_{14} = -\Gamma_{14}\,\mathrm{diag}\,(\tilde{u}\sin\theta, 0, \tilde{w}\cos\theta\cos\phi \quad (29)$$
$$\tilde{p}\cos\theta\cos\phi, \tilde{q}\cos\theta\cos\phi, \tilde{r}\sin(\theta))$$

$$\dot{U}_{15} = -\Gamma_{15}\,\mathrm{diag}\,(0, \tilde{v}\cos\theta\sin\phi, \quad (30)$$
$$0, \tilde{p}\cos\theta\sin\phi, \tilde{q}\sin\theta, \cos(\theta)\sin(\phi)),$$

respectively. Finally, for the inertia matrix M it is assigned the law

$$\dot{U}_{16} = -\Gamma_{16} \begin{bmatrix} \tilde{u}d_1 & \tilde{u}d_2 & \tilde{u}d_3 & \tilde{u}d_4 & \tilde{u}d_5 & \tilde{u}d_6 \\ \tilde{v}d_1 & \tilde{v}d_2 & \tilde{v}d_3 & \tilde{v}d_4 & \tilde{v}d_5 & \tilde{v}d_6 \\ \tilde{w}d_1 & \tilde{w}d_2 & \tilde{w}d_3 & \tilde{w}d_4 & \tilde{w}d_5 & \tilde{w}d_6 \\ \tilde{p}d_1 & \tilde{p}d_2 & \tilde{p}d_3 & \tilde{p}d_4 & \tilde{p}d_5 & \tilde{p}d_6 \\ \tilde{q}d_1 & \tilde{q}d_2 & \tilde{q}d_3 & \tilde{q}d_4 & \tilde{q}d_5 & \tilde{q}d_6 \\ \tilde{r}d_1 & \tilde{r}d_2 & \tilde{r}d_3 & \tilde{r}d_4 & \tilde{r}d_5 & \tilde{r}d_6 \end{bmatrix}, \quad (31)$$

where d_i is the element i of the vector $\mathbf{d}$ in (25).

Due to space constrain, the convergence of the adaptive laws are not shown here. The reader can however refer to (Jordán and Bustamante, 2006) for finding similar arguments for a formal proof.

3.3 State/disturbance observer

The control performance can be considerably enhanced if the thruster dynamics is involved in the controller design. The way to do this includes the estimation of the drivers states and input so as to employ the inverse thruster dynamics in the controller design. Therefore, we summarize the algorithm presented in (Jordán *et al.*, 2005) on the basis of (13)-(16). First, let us look for a reference thrust vector instead of (13), but calculated directly by

$$\mathbf{f}_r = \mathcal{C}\left(\hat{\mathbf{n}}_r\right), \quad (32)$$

with $\hat{\mathbf{n}}_r$ being a reference rpm vector with elements $\hat{n}_r$ for each thruster. As $\hat{\mathbf{n}}_r$ is unknown, it is estimated as perturbation. To this end, let the state model for thrusters be

$$\dot{\mathbf{x}} = A\mathbf{x} + \mathbf{b}\,n_r \quad (33)$$
$$n = \mathbf{c}^T\mathbf{x}, \quad (34)$$

and an estimation of the state

$$\dot{\hat{\mathbf{x}}} = A\hat{\mathbf{x}} + \mathbf{b}\,\hat{n}_r + \mathbf{k}_x\,(n_{ideal} - \hat{n}), \quad (35)$$

with

$$\mathbf{f}_{ideal} = B^T(BB^T)^{-1}\mathbf{F}_t \quad (36)$$
$$n_{ideal} = \mathcal{C}^{-1}(f_{ideal}). \quad (37)$$

So the perturbation results estimated as

$$\tilde{n}_r = -\left(k_n\mathbf{c}^T + k_{\dot{n}}\mathbf{c}^T A\right)\check{\mathbf{x}}, \quad (38)$$

with $\check{\mathbf{x}} = \mathbf{x} - \hat{\mathbf{x}}$ the state error, which in turn accomplishes

$$\dot{\check{\mathbf{x}}} = \left(A - \mathbf{k}_x\mathbf{c}^T - \mathbf{b}\,\left(k_n\mathbf{c}^T + k_{\dot{n}}\mathbf{c}^T A\right)\right)\check{\mathbf{x}}, \quad (39)$$

in where its parameters are

$$k_{\dot{n}} = \frac{1}{b_{n-1}}$$
$$\mathbf{k}_{\hat{x}} = -\left[\frac{-a_{n-1}}{b_{n-1}} + k_n, \frac{1}{b_{n-1}}, 0, ..., 0\right]. \quad (40)$$

Hence, if $\left(A - \mathbf{k}_x\mathbf{c}^T - \mathbf{b}\left(k_n\mathbf{c}^T + k_{\dot{n}}\mathbf{c}^T A\right)\right)$ is Hurwitz, then both errors accomplish

$$\check{\mathbf{x}},\, \tilde{n}_r \to 0 \text{ for } t \to \infty. \quad (41)$$

In (Jordán *et al.*, 2005) there are given examples for the application of the observer and guidelines to tune the matrix A.

Finally, instead of (13), (32) is applied for the adaptive control. This also contains the information of the control action $\mathbf{F}_t$ through (36).

3.4 Reference flight path for sampling

The reference trajectory for flying and picking up a targeted object from the sea bottom is particularly defined in such a way that the landing and takeoff of the vehicle on the sea bottom be done softly despite a mass change in this operation. Other point to be considered is that usually the on-board camera to operate the manipulator is on the front and directed to the targeted object. So the vehicle has to approach with a nonzero pitch angle, grab the object and retreat finally without collision.

A suitable flight path to this end could consist in a rectilinear approach to the target with asymptotic null velocity, then of a pause on a lower fixed point over the bottom till the object is seized, next of a retreat backwards with increasing velocity, and finally a turn around itself or on a helicoid to recover the initial rectilinear stretch of the trajectory. This would ensure successfully and optimally the end of the mission.

On the other hand, the execution of such a path on part of the operator would demand his/her full skillful if the goal has to be performed rapidly and carefully due to the significant perturbation caused in pitch and heave modes mainly.

Our goal next is to performed this tracking automatically and adaptively with the approach developed previously.

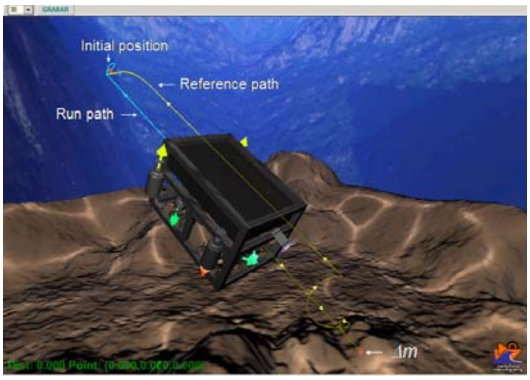

Fig. 2 - Adaptive control of an AUV along a reference fly path for sampling

4. NUMERICAL SIMULATIONS

In this section, some numerical simulations are presented to illustrate the features of our adaptive approach. A reference trajectory such as that described previously is applied (see Fig. 2). At the beginning, no information is available of the large amount of system parameters in (6)-(12). A 11-meters stretch is covered by the vehicle from an upper initial position in order to pick up a mass on the sea bed and afterwards return to the start position. Different masses were tested, namely $1(Kg)$ and $2,25(Kg)$, taking care therein that no thruster saturation be produced in the vehicle state when being at rest.

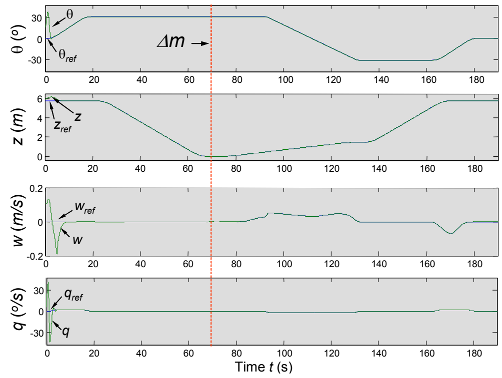

Fig. 3 - Evolution of pitch and heave modes for a mass change $1(Kg)$ at $t = 71(s)$

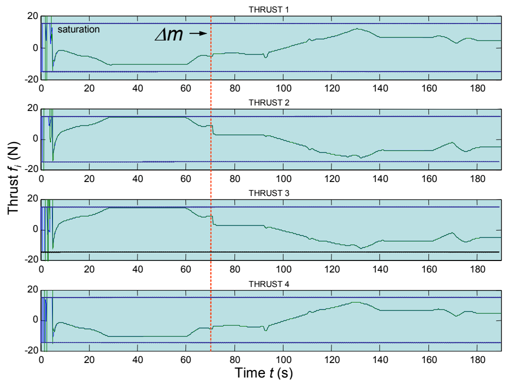

Fig. 4 - Vertical thrusts for a mass change of $1(Kg)$ at $t = 71(s)$

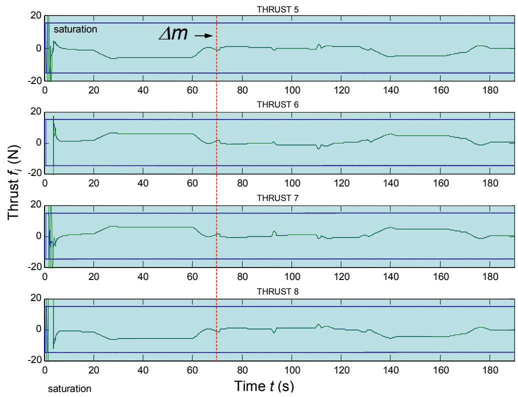

Fig. 5 - Horizontal thrusts for a mass change $1(Kg)$ at $t = 71(s)$

Fig. 3 depicts the main modes of motion for a mass change of $1(Kg)$. One sees that after a short commissioning phase of the adaptive control and observer, both the pitch and heave acquires the desired geometric and cinematic paths without appreciable error. This is also noticed for the time point when a mass is picked up by a simulacrum of the manipulator operation. On the other side, the 8 thrusts show signs of a greater sensibility than the states at this point. This is illustrated in

Figs. 4 and 5 for vertical and horizontal thrusters, respectively. The tenor of this response in more intense for a larger mass change of about $2.25(Kg)$ (not shown in this paper). Finally, Fig. 6 characterizes the evolution of one of the numerous controller parameters, just one physically involved in the mass change. Despite the abrupt change of mass, the adaptive law leads this parameter slowly to a steady-state value.

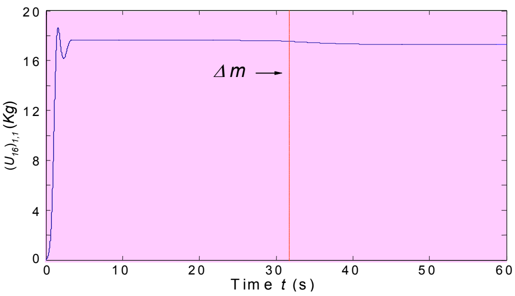

Fig. 6 - Evolution of the element $(1,1)$ of U_{16} for a mass change of $2.25(Kg)$ at $t = 31(s)$

5. CONCLUSIONS

A novel approach to direct adaptive control that combines a speed-gradient algorithm with a state/disturbance observer is presented for step-wise mass-varying. The control employs a coordinate system on a fixed known point instead of the mass center. This enables to generate adaptive laws for any dynamics change related to inertia, damping and hydrodynamics variations. In order to achieve high performances of the transient control behavior, the thruster dynamics is incorporated using an inverse dynamics technique and observer of the unknown states and input of the drivers using the vehicle states and the control action. A suitable flight path for sampling with manipulator is conceived for reference trajectory generation.

An illustration of the features of the approach in 6 degrees of freedom is accomplished by simulations of a case study. Results depict slight perturbations of the states during mass changes, not however the same in the thrusts, which show significant staged variations reacting sensitively to these disturbances. Also all changes in the multiple controller parameters are moderate. The all-round transient behavior of the adaptive loop is extremely short, travelling to the steady state rapidly with practically null tracking errors.

Future work is directed to construct minimal-time controls on geometric flight paths using automatic velocity generation.

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