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A MODULAR CONTROL LAW FOR UNDERWATER VEHICLE-MANIPULATOR SYSTEMS ADAPTING ON A MINIMUN SET OF PARAMETERS

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Abstract: The problem of controlling Underwater Vehicle-Manipulator Systems (UVMSs) is addressed in this paper. The serial-chain structure of such systems is exploited in order to formulate a control law based on the Virtual Decomposition approach. Each single body in the system is then controlled with a suitable adaptive control law based on a minimum number of parameters. The proposed approach results in a modular control scheme which simplifies application to multibody systems with a large number of links, reduces the required computational burden, and allows efficient implementation on distributed computing architectures. Furthermore, the occurrence of kinematic and representation singularities is overcome, respectively, by expressing the control law in body-fixed coordinates and representing the attitude via the unit quaternion. To show the effectiveness of the proposed control strategy, a full-degree-of-freedom simulation case study is developed for a vehicle in carrying a six-degrees-of-freedom manipulator. *Copyright ©2002 IFAC*

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1. INTRODUCTION

Underwater tasks involving an autonomous vehicle equipped with a manipulator are challenging control problems involving nonlinear, coupled, and high-dimensional systems. As typical in robotics, the execution of such tasks can be formulated in terms of a control problem for the manipulator's end-effector motion.

In recent years, control strategies based on perfect compensation of the UVMS' dynamics have been proposed (Canudas de Wit *et al.* (1998)); however, the assumption of exact knowledge of the system dynamics is unrealistic for underwater systems, mainly due to the hydrodynamic terms strongly depending on the environmental conditions.

To overcome this problem, adaptive control laws have then been proposed, e.g., (McLain *et al.* (1996), Antonelli *et al.* (1998)). These adaptive control approaches, Lagrangian based, regarded the UVMS as a whole, giving rise to high-dimensional problems: differently from the case of earth-fixed manipulators, in the case of UVMS it is not possible to achieve a reduction of the number of dynamic parameters to be adapted, since the base of the manipulator —i.e., the vehicle— has full mobility. As a matter of fact, the computational load of Lagrangian-based control algorithms grows as much as the fourth-order power of the number of the system's degrees of freedom. For this reason, practical application of adaptive control to UVMS has been limited, even in simulation, to vehicles carrying arms with very few joints (i.e., two or three) and usually performing planar tasks. An adaptive, non-regressor-based control law is proposed in (Sarkar *et al.* (1999)); in this case, even for the basic dynamic terms the model knowledge is not exploited to compensate for.

In (Antonelli *et al.* (1999, 2001c)), based on the work in (Zhu *et al.* (1997)), an adaptive control law in which the serial-chain structure of the UVMS is exploited is proposed. The overall motion control problem is decomposed in a set of elementary control problems regarding the motion of each rigid body in the system, namely the manipulator's links and the vehicle. For each body, a control action is designed to assign the desired motion, to adaptively compensate for the body dynamics, and to counteract force/moment exchanged with its neighbourhoods along the chain.

On the other hand, in Antonelli *et al.* (2001, 2001b) it is shown, that, for a single rigid body, a suitable regressor-based adaptive control law get improvement in the tracking error by considering the adaptation on the sole persistent terms, i.e., the current and the restoring forces.

In this paper, thus, this two approaches are merged in order to get benefit from both approaches. The resulting control scheme has a modular structure which greatly simplifies its application to systems with a large number of links; furthermore, it reduces the required computational burden by replacing one high-dimensional problem with many low-dimensional ones, finally allows efficient implementation on distributed computing architectures.

Remarkably, the control law is expressed in terms of body-fixed coordinates so as to overcome the occurrence of kinematic singularities (Antonelli and Chiaverini (2001d)). Moreover, a non-minimal representation of the orientation —i.e., the unit quaternion (Roberson and Schwertassek (1988))— is used in the control law; this allows overcoming the occurrence of representation singularities.

The proposed control scheme is tested in a numerical case study. A manipulation task is assigned in terms of a desired position and orientation trajectory for the end effector of a six-degree-of-freedom manipulator mounted on a six-degree-of-freedom vehicle. Then, the system's behavior under the proposed control law is verified in simulation.

2. MODELING

Consider a serial chain (the *manipulator*) composed by n rigid bodies (the *links*) connected via mechanical joints; the serial chain is mounted on a floating base (the *vehicle*). The vehicle and the manipulator's links are numbered from 0 (the vehicle) to n (the last link, also termed the *end effector*). Hence, the total number of dofs for the considered mechanical structure is $n + 6$.

A reference frame $\mathcal{T}_i$ ($i = 0, \ldots, n$) is attached to each body according to the Denavit-Hartenberg formalism, while $\mathcal{T}_e \equiv \mathcal{T}_{n+1}$ is the terminal frame attached to the end-effector. Also, an earth-fixed inertial reference frame $\mathcal{T}$ is considered. Hereafter, a superscript will denote the frame to which a vector is referred, the superscript will be dropped for quantities referred to the inertial frame.

The (6×1) vector of the total generalized force (i.e., force and moment) acting on the ith body and the (6×1) vector of the generalized velocities (i.e., linear and angular components) are given by

$$\boldsymbol{h}_{t,i}^i = \boldsymbol{h}_i^i - \boldsymbol{U}_{i+1}^i \boldsymbol{h}_{i+1}^{i+1}, \quad i = 0, \ldots, n \tag{1}$$

$$\boldsymbol{\nu}_{i+1}^{i+1} = \left(\boldsymbol{U}_{i+1}^i\right)^{\mathrm{T}} \boldsymbol{\nu}_i^i + \dot{q}_{i+1} \boldsymbol{z}_i^{i+1}, i = 0, \ldots, n-1 \tag{2}$$

where $\boldsymbol{h}_i^i$ is the generalized force exerted by body $i-1$ on body i, $\boldsymbol{h}_{i+1}^{i+1}$ is the generalized force exerted by body $i+1$ on body i, $\boldsymbol{\nu}_i^i$ is the velocity of body i. The matrix $\boldsymbol{U}_{i+1}^i \in \mathbb{R}^{6\times 6}$ is defined as

$$\boldsymbol{U}_{i+1}^i = \begin{bmatrix} \boldsymbol{R}_{i+1}^i & \boldsymbol{O}_3 \\ \boldsymbol{S}(\boldsymbol{r}_{i,i+1}^i)\boldsymbol{R}_{i+1}^i & \boldsymbol{R}_{i+1}^i \end{bmatrix}.$$

where $\boldsymbol{R}_{i+1}^i \in \mathbb{R}^{3\times 3}$ is the rotation matrix from frame $\mathcal{T}_{i+1}$ to frame $\mathcal{T}_i$, $\boldsymbol{S}(\cdot) \in \mathbb{R}^{3\times 3}$ is the skew-symmetric matrix operator performing the cross product between two vectors in $\mathbb{R}^{3\times 3}$, $\boldsymbol{r}_{i,i+1}^i$ is the vector pointing from the origin of $\mathcal{T}_i$ to the origin of $\mathcal{T}_{i+1}$ and $\boldsymbol{O}_3$ is the (3×3) null matrix.

The equations of motion of each rigid body can be written in the body-fixed reference frame in the form:

$$\boldsymbol{M}_i \dot{\boldsymbol{\nu}}_i^i + \boldsymbol{C}_i(\boldsymbol{\nu}_i^i)\boldsymbol{\nu}_i^i + \boldsymbol{D}_i(\boldsymbol{\nu}_i^i)\boldsymbol{\nu}_i^i + \boldsymbol{g}_i(\boldsymbol{R}_i) = \boldsymbol{h}_{t,i}^i, \tag{3}$$

where $\boldsymbol{\nu}_i^i \in \mathbb{R}^6$ is the vector of generalized velocity, i.e., linear and angular velocities, $\boldsymbol{R}_i$ is the rotation matrix expressing the orientation of $\mathcal{T}_i$ with respect to the inertial reference frame, $\boldsymbol{M}_i \in \mathbb{R}^{6\times 6}$ is the constant mass matrix, $\boldsymbol{C}_i(\boldsymbol{\nu}_i^i)\boldsymbol{\nu}_i^i \in \mathbb{R}^6$ is the vector of Coriolis and centrifugal terms, $\boldsymbol{D}_i(\boldsymbol{\nu}_i^i)\boldsymbol{\nu}_i^i \in \mathbb{R}^6$ is the vector of friction and $\boldsymbol{g}_i(\boldsymbol{R}_i) \in \mathbb{R}^6$ is the vector of gravitational generalized forces.

In case of underwater systems, $\boldsymbol{D}_i(\boldsymbol{\nu}_i^i)\boldsymbol{\nu}_i^i$ includes the hydrodynamic damping terms, while $\boldsymbol{g}_i(\boldsymbol{R}_i)$ includes the generalized buoyant forces (Yuh (1990), Fossen (1994)) and is absent for space systems (i.e., in microgravity environment).

According to the property of linearity in the parameters eq. (3) can be rewritten as:

$$\boldsymbol{Y}(\boldsymbol{R}_i, \boldsymbol{\nu}_i^i, \dot{\boldsymbol{\nu}}_i^i) \cdot \boldsymbol{\theta}_i = \boldsymbol{h}_{t,i}^i \tag{4}$$

where $\boldsymbol{\theta}_i \in \mathbb{R}^w$ is the vector of dynamic parameters of the ith rigid body. Notice, that the dimension of the vector $\boldsymbol{\theta}_i$ is $w = 7$ for a single rigid body in the space, $w = 13$ for links of ground-fixed or space robotic structures (considering only static and viscous friction), while w may be very large (i.e., $w \simeq 100$ if all hydrodynamic and damping terms are taken into account) for a rigid body moving in a fluid as shown in Healey and Lienard (1993) (i.e., for underwater systems).

In case of the presence of the ocean current, it is necessary to consider the relative velocity $\boldsymbol{\nu}_{r,i}^i = \boldsymbol{\nu}_i^i - \boldsymbol{R}_i^{\mathrm{T}} \boldsymbol{\nu}_c$ in the derivation of the equations of motion in (3). The vector $\boldsymbol{\nu}_c$ is the current, usually considered constant, expressed in the inertial frame.

The torque (force) τ_i acting at the ith joint of the manipulator can be obtained by projecting $\boldsymbol{h}_i$ on the corresponding joint axis, i.e.

$$\tau_i = \left(\boldsymbol{z}_{i-1}^i\right)^{\mathrm{T}} \boldsymbol{h}_i^i, \tag{5}$$

where $\boldsymbol{z}_{i-1}^i = \boldsymbol{R}_i^{\mathrm{T}} \boldsymbol{z}_{i-1}$ is the z-axis of the frame $\mathcal{T}_{i-1}$ expressed in the frame $\mathcal{T}_i$. The generalized force acting on the vehicle is instead given by the (6×1) vector $\boldsymbol{h}_{t,0}^0$.

The Jacobian $\boldsymbol{J}(\boldsymbol{R}_0, \boldsymbol{q})$ of the structure relates the end-effector generalized force/velocities to the *system* force/velocities. In detail, let define as $\boldsymbol{\zeta} \in \mathbb{R}^{6+n}$ the aggregated velocity vector

$$\boldsymbol{\zeta} = \left[\boldsymbol{\nu}_0^{0^{\mathrm{T}}} \quad \dot{\boldsymbol{q}}^{\mathrm{T}}\right]^{\mathrm{T}}, \tag{6}$$

where $\boldsymbol{q} = [q_1 \quad \ldots \quad q_n]^{\mathrm{T}}$ and q_i is the angular (linear) displacement of the ith mechanical joint which connects the $i-1$th and ith rigid bodies in the system. Then, the end-effector generalized velocity $\boldsymbol{\nu}_e$ (i.e., the velocity of the last link of the chain) is given by

$$\boldsymbol{\nu}_e = \boldsymbol{J}\boldsymbol{\zeta}. \tag{7}$$

Moreover, by invoking a kinetostatics duality concept, it can be recognized that the transpose of the Jacobian relates the generalized force acting at the end effector $\boldsymbol{h}_e$ with the aggregated generalized force ($\boldsymbol{\tau} = [\tau_1 \quad \ldots \quad \tau_n]^{\mathrm{T}}$)

$$\boldsymbol{h} = \left[\boldsymbol{h}_0^{0^{\mathrm{T}}} \quad \boldsymbol{\tau}^{\mathrm{T}}\right]^{\mathrm{T}}, \tag{8}$$

via the relationship dual to (7)

$$\boldsymbol{h} = \boldsymbol{J}^{\mathrm{T}} \boldsymbol{h}_e. \tag{9}$$

3. CONTROL LAW

Typically a task for a serial-chain mechanical structure is assigned in terms of end-effector desired quantities. Let $\boldsymbol{p}_{d,e}(t) \in \mathbb{R}^3$ be the desired end-effector position trajectory and $\mathcal{Q}_{d,e}(t)$ the desired end-effector orientation; let also denote by $\boldsymbol{\nu}_{d,e}^e \in \mathbb{R}^6$ and $\dot{\boldsymbol{\nu}}_{d,e}^e \in \mathbb{R}^6$ the desired generalized velocity and acceleration, respectively.

The corresponding desired quantities for the vehicle and the manipulator $\boldsymbol{p}_{d,0}(t)$, $\mathcal{Q}_{d,0}(t)$, $\boldsymbol{q}_d(t)$, $\boldsymbol{\nu}_{d,0}^0(t)$, $\dot{\boldsymbol{q}}_d(t)$, $\dot{\boldsymbol{\nu}}_{d,0}^0(t)$, $\ddot{\boldsymbol{q}}_d(t)$ can be obtained by resorting to an inverse kinematics algorithm as in Antonelli and Chiaverini (2001d) based on the inversion of the differential kinematics relationship (7). From the quantities output by the inverse kinematics algorithm it is possible to compute $\boldsymbol{p}_{d,i}(t)$, $\mathcal{Q}_{d,i}(t)$, $\boldsymbol{\nu}_{d,i}^i(t)$ and $\dot{\boldsymbol{\nu}}_{d,i}^i(t)$ for $i = 1 \ldots n$ via forward kinematics of the manipulator.

Let define the reference velocity vectors

$$\begin{aligned} \boldsymbol{\nu}_{r,0}^0 &= \boldsymbol{\nu}_{d,0}^0 + \begin{bmatrix} \lambda_{p,0}\boldsymbol{I}_3 & \boldsymbol{O}_3 \\ \boldsymbol{O}_3 & \lambda_{o,0}\boldsymbol{I}_3 \end{bmatrix} \boldsymbol{e}_0, \\ \dot{q}_{r,i} &= \dot{q}_{d,i} + \lambda_i \tilde{q}_i, \quad i = 1, \ldots, n \\ \boldsymbol{\nu}_{r,i+1}^{i+1} &= \left(\boldsymbol{U}_{i+1}^i\right)^{\mathrm{T}} \boldsymbol{\nu}_{r,i}^i + \dot{q}_{r,i+1} \boldsymbol{z}_i^{i+1} \quad i = 0, \ldots, n-1, \end{aligned} \tag{10}$$

where $\lambda_{p,0}, \lambda_{o,0}, \lambda_i$ are positive scalar gains to be properly designed. In eq. (10), the vector $\boldsymbol{e}_0 \in \mathbb{R}^6$ collects the vehicle position and orientation tracking errors and is defined as

$$\boldsymbol{e}_0 = \begin{bmatrix} \boldsymbol{R}_0^{\mathrm{T}} \tilde{\boldsymbol{p}}_0 \\ \tilde{\boldsymbol{\varepsilon}}_0^0 \end{bmatrix}, \tag{11}$$

where $\tilde{\boldsymbol{\varepsilon}}_0^0 \in \mathbb{R}^3$ is the vector part of the unit quaternion $\widetilde{\mathcal{Q}}_0$.

It is useful considering the following variables

$$\begin{aligned} \boldsymbol{s}_i^i &= \boldsymbol{\nu}_{r,i}^i - \boldsymbol{\nu}_i^i & i &= 0, \ldots, n \\ s_{q,i} &= \dot{q}_{r,i} - \dot{q}_i & i &= 1, \ldots, n \\ \boldsymbol{s}_q &= [s_{q,1} \ \ldots \ s_{q,n}]^{\mathrm{T}}. \end{aligned} \tag{12}$$

In the following it is assumed that only a nominal estimate $\hat{\boldsymbol{\theta}}_i$ of the vector of dynamic parameters is available for the ith rigid body. Hence, a suitable update law for the estimates has to be adopted so as to ensure asymptotic tracking of the desired trajectories.

The proposed control law is based on the computation of the *required* generalized force for each rigid body in the system. Then, the input torques for the manipulator and the input generalized force for the vehicle are computed from the required forces according to (1) and (5). For the ith rigid body ($i = 0, \ldots, n$) the required force has the following expression

$$\boldsymbol{h}_{r,i}^i = \boldsymbol{Y}'\left(\boldsymbol{R}_i, \boldsymbol{\nu}_i^i, \boldsymbol{\nu}_{r,i}^i, \dot{\boldsymbol{\nu}}_{r,i}^i\right) \hat{\boldsymbol{\theta}}_i + \boldsymbol{K}_{v,i} \boldsymbol{s}_i^i. \tag{13}$$

In Antonelli *et al.* (2001, 2001b) it is shown that, using a specific regressor structure allows to have a suitable adapting strategy using a minimal set of dynamic parameters. The regressor used in the following has the structure:

$$\boldsymbol{Y}' = \begin{bmatrix} \boldsymbol{O}_{3\times3} & \boldsymbol{R}_i & \boldsymbol{O}_{3\times3} \\ \boldsymbol{S}(\boldsymbol{R}_i\boldsymbol{z}) & \boldsymbol{O}_{3\times3} & \boldsymbol{R}_i \end{bmatrix}, \qquad (14)$$

and it based on 9 parameters for each rigid body. The control generalized force is given by

$$\boldsymbol{h}^i_{c,i} = \boldsymbol{h}^i_{r,i} + \boldsymbol{U}^i_{i+1}\boldsymbol{h}^{i+1}_{c,i+1} \qquad (15)$$

with $\boldsymbol{K}_{v,i} > \boldsymbol{O}$. The parameters estimate $\hat{\boldsymbol{\theta}}_i$ is dynamically updated via

$$\dot{\hat{\boldsymbol{\theta}}}_i = \boldsymbol{K}^{-1}_{\theta,i}\boldsymbol{Y}^{\mathrm{T}}\left(\boldsymbol{R}_i, \boldsymbol{\nu}^i_i, \boldsymbol{\nu}^i_{r,i}, \dot{\boldsymbol{\nu}}^i_{r,i}\right)\boldsymbol{s}^i_i \qquad (16)$$

with $\boldsymbol{K}_{\theta,i} > \boldsymbol{O}$.

Finally, the control torque provided by the actuator at the ith manipulator's joint can be computed as follows

$$\tau_i = \left(\boldsymbol{z}^i_{i-1}\right)^{\mathrm{T}}\boldsymbol{h}^i_{c,i}, \qquad (17)$$

while the generalized force provided by the actuators on the vehicle is computed as

$$\boldsymbol{h}^0_{c,0} = \boldsymbol{h}^0_{r,0} + \boldsymbol{U}^0_1\boldsymbol{h}^1_{c,1}. \qquad (18)$$

It can be recognized that the structure of the control architecture is based on the forward and backward ricorsion of the Newton-Euler equations for the rigid bodies constituting the UVMS. The kinematic errors are forward propagated along the structure while the control forces backward propagated. This allows to use a generic control law for a single rigid body in 6-dofs.

To summarize, the following step are necessary to the implementation of the control law:

(1) compute the desired trajectories for the rigid bodies composing the system;
(2) from $i = 0, \ldots, n$ compute the error variables $\boldsymbol{s}^i_i$ based on the equations (10)-(12);
(3) from $i = n, \ldots, 0$ compute the control force $\boldsymbol{h}^i_{c,i}$ based on eq. (15) and update the dynamic parameters by (16);
(4) project the (6×1) generalized force on the actuating direction based on (17) (in case of presence of a moving base use (18)).

It is worth noticing that, from a mathematical point of view, an integral action on a UVMS can be obtained simply integrating the errors along the actuating directions: $6 + n$ in this case. This solution, of course, would not be efficient. Moreover a full UVMS regressor would have $\approx 100 * (n + 1)$ parameters. With the proposed approach, the number of parameters to adapt is $9 * (n + 1)$. Moreover, the improvement of the adaptation action can still be observed.

The stability analysis of the proposed controller follows the guidelines in Antonelli *et al.* (2001c, 2001b).

4. SIMULATIONS

Numerical simulations have been performed to show the effectiveness of the proposed control law. The UVMS simulator, developed by using the Matlab 5.3, Simulink 3.0 environment, is described in Antonelli and Chiaverini (2000).

The vehicle data are taken from Healey and Lienard (1993) and are referred to the experimental Autonomous Underwater Vehicle NPS AUV II. In this paper a six-dof manipulator with rotational joints has been considered which is mounted under the vehicle's body. The manipulator structure and the dynamic parameters are those of the Smart-3S manufactured by COMAU.

The dynamic model of the system involves a large number of dynamic parameters, considering a simplified drag effects for the manipulator links, the simulation uses $\approx$ 400 dynamic parameters. As detailed in Section 3, the overall number of parameters of the controller is $9*(n+1) = 63$. Moreover, the software to implement the controller is modular, the same function is used to compensate for all the rigid bodies with different parameters as inputs. This makes easier the debugging procedure.

The desired end-effector path is a straight line with length of 35 cm, to be executed 4 times according to a 5th order polynomial time law; the duration of each cycle is 4 s. The desired end-effector orientation is constant along the commanded path. The vehicle is commanded to keep its initial position and orientation during the task execution. Therefore, the inverse kinematics is needed to compute the sole joint vectors $\boldsymbol{q}_d(t)$, $\dot{\boldsymbol{q}}_d(t)$ and $\ddot{\boldsymbol{q}}_d(t)$ in real time, and thus only the inverse of the (6×6) manipulator Jacobian $\boldsymbol{J}_m$ is required in the inverse kinematics algorithm.

A constant ocean current affect the motion with the following components:

$$\boldsymbol{\nu}_c = [\,0.1 \quad 0.3 \quad 0 \quad 0 \quad 0 \quad 0\,]^{\mathrm{T}} \quad \mathrm{m/s}. \qquad (19)$$

As reported in Antonelli *et al.* (2001, 2001b), some of the parameters of the controllers are related to the knowledge of the mass and the first moment of gravity/buoyancy. Their initial estimate are set so as to give an estimation error larger then 20% of the true values. The other parameters are related to the presence of the current. Those, will be initialized to the null value.

The control law parameters have been set to:

$$\boldsymbol{\Lambda}_0 = \mathrm{blockdiag}\{0.4\boldsymbol{I}_3,\ 0.6\boldsymbol{I}_3\}$$
$$\boldsymbol{\Lambda}_{i=1,6} = \mathrm{blockdiag}\{0.9\boldsymbol{I}_3,\ 0.9\boldsymbol{I}_3\}$$

$$\begin{aligned} \boldsymbol{K}_{v,0} &= \text{blockdiag}\{9100\boldsymbol{I}_3,\ 9800\boldsymbol{I}_3\} \\ \boldsymbol{K}_{v,i=1,6} &= \text{blockdiag}\{600\boldsymbol{I}_3,\ 800\boldsymbol{I}_3\} \\ \boldsymbol{K}_{\theta,0} &= 100\boldsymbol{I}_9 \\ \boldsymbol{K}_{\theta,i=1,6} &= 40\boldsymbol{I}_9, \end{aligned} \tag{20}$$

where $\boldsymbol{I}_9$ is the (9×9) identity matrix.

The results are reported in Figures 1–2 in terms of end-effector position/orientation tracking errors; it can be recognized that, in spite of the demanding task commanded to the system, the errors are kept small in the transients and reach zero values at steady state.

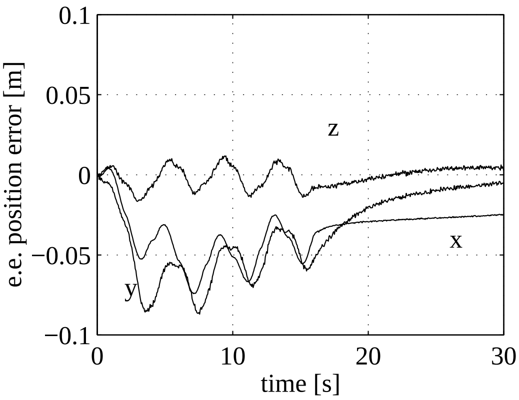

Fig. 1. End-effector position error.

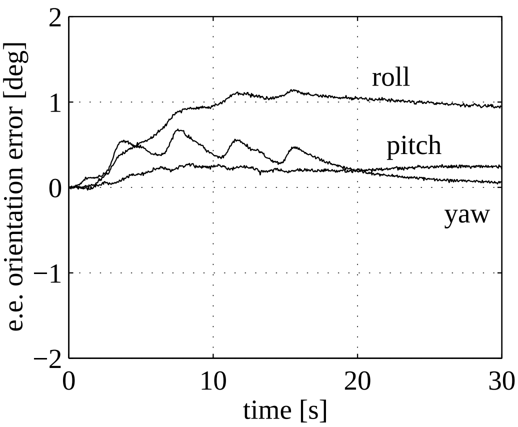

Fig. 2. End-effector orientation error.

Moreover, the results in Figures 3–5 show that the control force and moments acting on the vehicle, as well as the control torques applied at the manipulator's joints, are kept limited along all the trajectory and are characterized by a smooth profile. It is worth noticing that, at the beginning of the task, the controller is not aware of the presence of the current; a compensation can be observed mainly along the x and y vehicle linear forces and moments.

In Figures 6–8, the vehicle position and orientation and the joint tracking errors are reported. The tracking errors along the yaw direction can be motivated by the effect of the current, its value is decreasing to the null value according to the control gains.

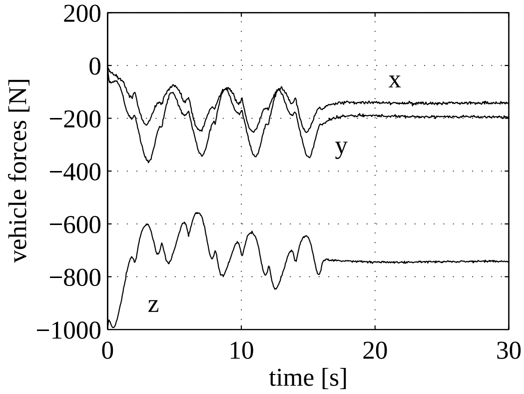

Fig. 3. Vehicle control forces.

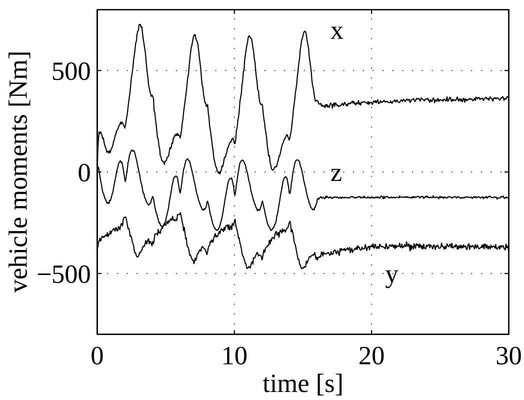

Fig. 4. Vehicle control moments.

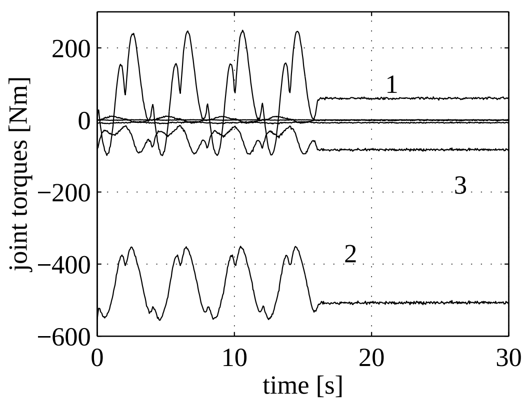

Fig. 5. Joint control torques.

5. CONCLUSIONS

In this paper a modular adaptive control scheme for the end-effector tracking problem of an UVMS has been proposed. The serial-chain structure of the system has been exploited to decompose the control law in a set of simpler control laws, each of them designed for a single rigid body in the system. The proposed approach results in a modular control scheme which can be conveniently applied to complex mechanical systems, helps in reducing the computational burden, and allows its implementation on distributed computing hardware. Each of the rigid body is controlled by means of a regressor based on a minimum set of parameters that counteract the persistent terms, i.e., the current and the restoring forces. Also,

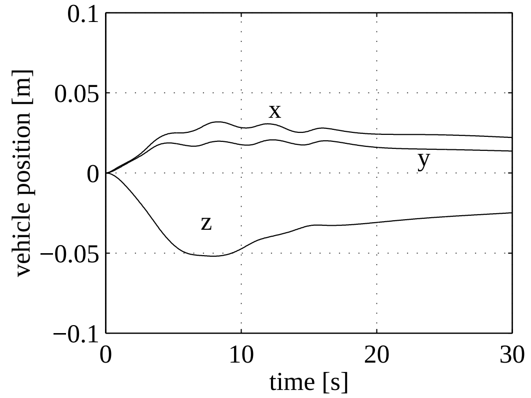

Fig. 6. Vehicle position.

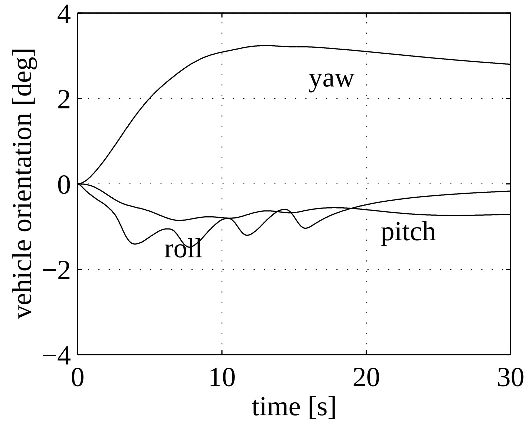

Fig. 7. Vehicle orientation.

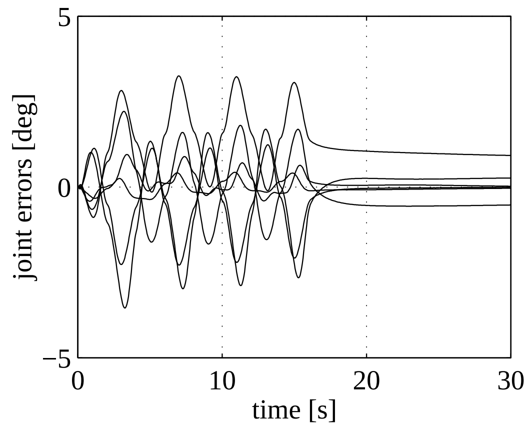

Fig. 8. Joint position errors.

the occurrence of kinematic and representation singularities is overcome by expressing the control law in body-fixed coordinates and representing the attitude via the unit quaternion. Finally, a simulation case study has been carried out for a vehicle in spatial motion equipped with a six-degrees-of-freedom manipulator. The obtained results confirm the effectiveness of the proposed scheme in terms of tracking errors and control effort.

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