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ADAPTIVE ROBUST CONTROLLER FOR A CONSTRAINED FREE-FLOATING SPACE MANIPULATOR

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Resumo – O controle robusto de um manipulador de base livre flutuante sujeito a restrições de posição e força é desenvolvido neste trabalho. O problema é formulado no espaço da tarefa e a dinâmica desconhecida do sistema é estimada por uma rede neural adaptativa. Um controlador não-linear $\mathscr{H}_\infty$ é aplicado para atenuar os efeitos de erros de estimativa e de perturbações externas. A estratégia desenvolvida não exige a medição de valores de aceleração da base livre flutuante e do braço. A eficácia da proposta é demonstrada por resultados de simulação.

Palavras-chave – Manipulador de base livre flutuante, sistemas restritos, controle $\mathscr{H}_\infty$ não-linear, redes neurais.

Abstract – The robust trajectory tracking control for a constrained free-floating space manipulator is treated in this paper. The problem is formulated in task-space and the system unknown dynamics is estimated by an adaptive neural network. A nonlinear $\mathscr{H}_\infty$ controller is applied to attenuate the effects of estimation errors and external disturbances. The presented method does not demand measured values of acceleration neither from the free-floating base nor from the arm. Simulation results showed the effectiveness of the proposed control strategy.

Keywords – Free-floating base manipulator, constrained systems, nonlinear $\mathscr{H}_\infty$ control, neural networks.

1. INTRODUCTION

Servicing on malfunctioning satellites are to become routine operations for robot manipulators in space. The problem defined in these applications involves three stages: the approach phase, the impact moment and the sustained contact tracking. The approach phase has been treated in many works and defines the problem of positioning the tool without, or before, touching the environment, [1–6]. The second phase demands controlling the initial impact and damping out the vibrations generated during the event, see for instance [7–9]. After the initial impact, sustained contact is desired in many operations. In these cases, not only the motion of the end-effector is required to follow a prescribed path, but also the force exerted by the end-effector is required to follow a pre-defined reference. In these constrained systems, forces and moments generated between the end-effector and the target must be controlled, rather than being treated as disturbances and rejected. Impedance control has been applied in [8,10,11] to solve this problem.

Considering a free-floating space manipulator, this work aims to deal with the sustained contact tracking phase of the problem. In order to conserve fuel and electrical power, the free-floating space manipulator allows its spacecraft to move freely in response to the manipulator motions, [12]. In virtue of the complexity of these systems and the hostile environment where they operate, it must be noted that parametric uncertainties may appear not only in the dynamic equation, but also in kinematic mapping from joint-space to task-space due to the absence of a fixed base. When the base is free-floating, the kinematic mapping from task-space to joint-space, where the control is executed, becomes non-unique because of non-integrable angular momentum conservation. This may cause non-existence of the reference trajectory in joint space.

Therefore, in this paper, a task-space based approach is developed in the aim of rejecting disturbances and parametric uncertainties while controlling both position and force of a free-floating space manipulator subject to environmental constraints. Using the Dynamically Equivalent Manipulator (DEM) approach, [13], to model the space manipulator, an adaptive neural network robust controller is proposed. Based on the results from [14], the intelligent system is applied to learn the dynamic behavior of the robotic system, which is considered totally unknown. A $\mathscr{H}_\infty$ performance criterion is applied to attenuate the effects of estimation errors and external disturbances. The proposal is evaluated on a simulated space robot.

The sequence of this paper is organized as follows: Section 2 presents the model description through the DEM approach leading to a reduced-order model for the constrained free-floating space manipulator; the neural network nonlinear $\mathscr{H}_\infty$ control design is presented in Section 3; and, finally, simulation results for a constrained two-link free-floating space manipulator are presented in Section 4.

2. PROBLEM FORMULATION

Let the space manipulator (SM) be an n-link serial-chain rigid manipulator mounted on a free-floating base. Let the Dynamically Equivalent Manipulator (DEM) be a $(n+1)$-link fixed-base manipulator whose first joint is spherical and passive and is located at the center of mass of the SM. The model of DEM is kinematically and dynamically equivalent to the SM dynamics. Considering the application, let the end-effector of the robot be in contact with a target satellite or an environmental constraint.

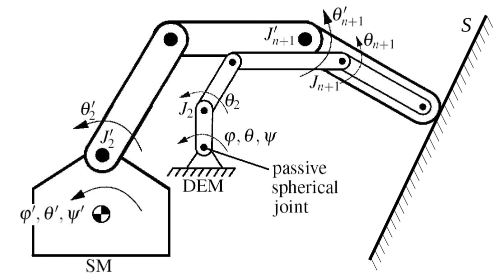

Figura 1: The space manipulator, its corresponding DEM and the environmental constraint.

Figure 1 shows the representation and the parameter notation for both SM and DEM. Let the SM parameters be identified by apostrophe ($'$), the links of the manipulators are numbered from 2 to $n+1$ and J_i is the joint connecting the $(i-1)$-th link and i-th link, θ_i is the rotation of the i-th link around joint J_i, and the Z-Y-Z Euler angles (φ, θ, ψ) represent the SM base attitude and the DEM first passive joint orientation. Let C_i be the center of mass of the i-th link, L_i be the vector connecting J'_i and C'_i, R_i be the vector connecting C'_i and J'_{i+1}, l_{ci} be the vector connecting J_i and C_i, and W_i be the vector connecting J_i and J_{i+1}. The constraint surface is represented by S.

Considering that no external forces and torques are applied on this system, and so the DEM operates in the absence of gravity, the kinematic and dynamical parameters of the DEM can be found from the SM parameters as in [13].

2.1 Robot Dynamics

Let the generalized coordinates $q = [\ \varphi \quad \theta \quad \psi \quad \theta_2 \quad \cdots \quad \theta_{n+1}\ ]^T$ be partitioned as $q = [\ q_b^T \quad q_m^T\ ]^T$, where the indexes b and m represent the passive spherical joint (base) and the active joints (manipulator), respectively.

Since the DEM modeling technique locates the inertial frame origin at the center of mass of the SM, the dependence of end-effector coordinates on base position, $p_b = [\ x_b \quad y_b \quad z_b\ ]$, is eliminated by integrating its equation of linear momentum, [12]. However, the dependence on base attitude cannot be eliminated since the angular momentum of the system cannot be analytically integrated to provide the base attitude as a function of the variables of manipulator joints. Hence, the vector of inertial position and orientation of the end-effector, $p = [\ \varphi_{ef} \quad \theta_{ef} \quad \psi_{ef} \quad x_{ef} \quad y_{ef} \quad z_{ef}\ ]$, is a function of free-floating base attitude q_b and of generalized coordinates of manipulator joints q_m.

From Lagrange theory, dynamic equations of the constrained DEM are given by

$$M(q_m)\ddot{q} + C(q_m, \dot{q})\dot{q} = B_\tau \tau + J(q)^T B_c f + \tau_d, \tag{1}$$

where $M(q_m) \in \mathbb{R}^{(n+3)\times(n+3)}$ is the symmetric positive definite inertia matrix, $C(q_m, \dot{q}) \in \mathbb{R}^{(n+3)\times(n+3)}$ is the matrix of Coriolis and centrifugal forces, $B_\tau \in \mathbb{R}^{(n+3)\times n}$ is the input matrix, $\tau \in \mathbb{R}^n$ is the torque vector acting upon the active joints of the DEM, $J(q) = \frac{\delta p}{\delta q} \in \mathbb{R}^{6\times(n+3)}$ is the joint-space to task-space Jacobian matrix, $B_c \in \mathbb{R}^{6\times n}$ is the constraint input matrix, $f \in \mathbb{R}^n$ denotes the task-space generalized forces on an environmental constraint exerted by the end-effector, and τ_d defines a finite energy unknown disturbance.

Remark 2.1 *Note that $B_\tau \tau$ defines a nonholonomic constraint imposed by the free-floating base. Since the nonholonomic constraint functions are nonintegrable, there is, in fact, no explicit restriction on the values of the configuration variables q. On the other hand, f denotes the force due to the reaction of a holonomic constraint, which then restricts the position of the end-effector and consequently the values of q.*

Parametric uncertainties can be introduced into the model considering $M(q_m)$, $C(q_m, \dot{q})$, $J(q)$ and f written as a nominal and a perturbed part:

$$\begin{aligned}
&M(q_m) = M_0(q_m) + \Delta M(q_m),\\
&C(q_m, \dot{q}) = C_0(q_m, \dot{q}) + \Delta C(q_m, \dot{q}),\\
&J(q) = J_0(q) + \Delta J(q),\\
&f = f_0 + \Delta f,
\end{aligned}$$

where $M_0(q_m)$, $C_0(q_m, \dot{q})$, $J_0(q)$ and f_0 are nominal matrices and $\Delta M(q_m)$, $\Delta C(q_m, \dot{q})$, $\Delta J(q)$ and Δf are the parametric uncertainties. Equation (1) can be rewritten as

$$M_0(q_m)\ddot{q} + C_0(q_m, \dot{q})\dot{q} = B_\tau \tau + J_0(q)^T B_c f_0 + \omega_\tau, \tag{2}$$

with $\omega_\tau = -\Delta M(q_m)\ddot{q} - \Delta C(q_m,\dot{q})\dot{q} + \Delta J(q)^T B_c f_0 + J_0(q)^T B_c \Delta f + \Delta J(q)^T B_c \Delta f + \tau_d$. For simplicity of notation, the index 0 referring to the nominal system will be suppressed in the sequence of the text and also the arguments of various functions will be omitted (e.g.,$M(\cdot)$,$C(\cdot,\cdot)$, etc.) from now on.

Considering that $det(J(q)) \neq 0$ during the proposed task, applying $\dot{p} = J(q)\dot{q}$ and its derivative, $\ddot{p} = \dot{J}(q)\dot{q} + J(q)\ddot{q}$, to (2), the dynamic equations of the constrained DEM in task-space are given by

$$M_{ef}\ddot{p} + C_{ef}\dot{p} = J^{-T}B_\tau\tau + B_c f + J^{-T}\omega_\tau, \tag{3}$$

where $M_{ef} = J^{-T}MJ^{-1} \in \mathbb{R}^{6\times 6}$ and $C_{ef} = J^{-T}(C - MJ^{-1}\dot{J})J^{-1} \in \mathbb{R}^{6\times 6}$. Observe that a premultiplication by a J^{-T} factor was also employed in (3) so that the dynamic equation formulated in task-space maintains the structure and properties found in joint-space. Thus, M_{ef} is symmetric positive definite and $N_{ef} = \dot{M}_{ef} - 2C_{ef}$ is skew-symmetric.

Based on control techniques for underactuated manipulators, [15], and considering that the DEM has $n < 6$ active joints, let's define $p = [\ p_u^T \quad p_a^T\ ]^T$ the vector of generalized coordinates of the system, with $p_u \in \mathbb{R}^{(6-n)}$ and $p_a \in \mathbb{R}^n$, where the indexes u and a represent the passive variables (which are let free during the control procedure) and the controlled variables, respectively. Matrices from equation (3) can be partitioned as:

$$M_{ef} = \begin{bmatrix} M_{ef_{uu}} & M_{ef_{ua}} \\ M_{ef_{au}} & M_{ef_{aa}} \end{bmatrix}, \quad C_{ef} = \begin{bmatrix} C_{ef_{uu}} & C_{ef_{ua}} \\ C_{ef_{au}} & C_{ef_{aa}} \end{bmatrix}, \quad J^{-T} = \begin{bmatrix} \bar{J}_{ef_{uu}} & \bar{J}_{ef_{ua}} \\ \bar{J}_{ef_{au}} & \bar{J}_{ef_{aa}} \end{bmatrix},$$

$$B_\tau = \begin{bmatrix} B_{\tau_u} \\ B_{\tau_a} \end{bmatrix}, \quad B_c = \begin{bmatrix} B_{c_u} \\ B_{c_a} \end{bmatrix}, \quad \omega_\tau = \begin{bmatrix} \omega_{\tau_u} \\ \omega_{\tau_a} \end{bmatrix}.$$

This decomposition should also preserve the properties of dynamic equation for the matrices $M_{ef_{aa}}$ and $C_{ef_{aa}}$ so that $M_{ef_{aa}} = M_{ef_{aa}}^T(q) > 0$ and $N_{ef_{aa}} = \dot{M}_{ef_{aa}} - 2C_{ef_{aa}}$ is skew-symmetric.

For the proposed application in this paper, define: $B_\tau = \begin{bmatrix} 0_{3\times n} \\ I_n \end{bmatrix}$, where $B_{\tau_u} = 0_{3\times n}$ denotes the free-floating base characteristic and $B_{\tau_a} = I_n$ is an input matrix for the torques acting upon the joints of the manipulator; and $B_c = \begin{bmatrix} 0_{(6-n)\times n} \\ I_n \end{bmatrix}$, where $B_{c_u} = 0_{(6-n)\times n}$ and $B_{c_a} = I_n$ is an input matrix for the generalized forces along the direction of the corresponding active coordinates of the space manipulator.

2.2 Constraint Modelling

The m constraints surface is described in task-space by the holonomic relationship

$$\phi(p_a) = 0_m, \tag{4}$$

where $\phi(p_a) : \mathbb{R}^n \to \mathbb{R}^m$ is a smooth function. The constraint forces are given by

$$f = J_c^T\lambda, \tag{5}$$

where $J_c = \frac{\delta\phi}{\delta p_a} \in \mathbb{R}^{m\times n}$ is the Jacobian matrix that relates the constraints to the controlled variables of the end-effector and $\lambda \in \mathbb{R}^m$ is a vector of generalized Lagrangian multipliers associated with the constraints.

The presence of m constraints causes the manipulator to lose m degrees of freedom, and, therefore, $n - m$ linearly independent coordinates are sufficient to characterize the constrained movement. So, with the aim of formulating a reduced order dynamics for the constrained system the following assumptions are made as in [14, 16].

1. Assume that the Jacobian matrix J_c has full row rank m for all $p_a \in \mathbb{R}^n$. Thus, p_a may be properly rearranged and partitioned into the form

$$p_a = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix},$$

where $x_1 \in \mathbb{R}^{(n-m)}$ describes the constrained motion of the space manipulator and $x_2 \in \mathbb{R}^m$ denotes the remainig degrees of freedom of the end-effector. According to the Implicit Function Theorem, there exists an open set $\Omega_c \subseteq \mathbb{R}^{(n-m)}$ and a unique C^1 mapping $\sigma : \Omega_c \to \mathbb{R}^m$ such that $x_2 = \sigma(x_1)$ and $\phi(x_1, \sigma(x_1)) = 0, \forall x_1 \in \Omega_c$.

2. Assume that $\Gamma = \frac{\delta\sigma(x_1)}{\delta x_1}$ is well defined for all manipulator operations of interest. Differentiating the constraint surface with respect to x_1 we obtain

$$\frac{\delta\phi}{\delta x_1} + \frac{\delta\phi}{\delta x_2}\frac{\delta\sigma(x_1)}{\delta x_1} = J_c \begin{bmatrix} I_{(n-m)} \\ \frac{\delta\sigma(x_1)}{\delta x_1} \end{bmatrix} = 0. \tag{6}$$

Define the Jacobian matrix of the variables transformation:

$$L(x_1) = \begin{bmatrix} I_{(n-m)} \\ \frac{\delta\sigma(x_1)}{\delta x_1} \end{bmatrix},$$

such that $\dot{p}_a = L(x_1)\dot{x}_1$.

3. Assume that the end-effector is already in contact with the constraint surface, and the control exerted over the constraint force is such that the force will always maintain the end-effector in contact with the constraint surface.

Considering that the constraint surface may be not perfectly rigid, frictionless or even that its geometric description may be not exactly known, parametric uncertainties may also be included into the constraint model. So, consider that

$$\begin{aligned}
&\phi(p_a) = \Delta\phi(p_a),\\
&J_c(p_a) = J_c(p_a) + \Delta J_c(p_a),\\
&x_2 = \sigma(x_1) + \Delta\sigma(x_1),\\
&L(x_1) = L(x_1) + \Delta L(x_1),
\end{aligned}$$

and assume that $\Delta\phi$, ΔJ_c, $\Delta\sigma$ and ΔL are implicit in Δf in equation (2).

2.3 Reduced Order Model

From equation (3), the description of the active dynamics of the space manipulator is given by

$$M_{ef_{aa}}\ddot{p}_a + C_{ef_{aa}}\dot{p}_a + M_{ef_{au}}\ddot{p}_u + C_{ef_{au}}\dot{p}_u = \bar{J}_{aa}\tau + J_c^T\lambda + \bar{J}_{aa}\omega_{\tau_a}. \tag{7}$$

Using the transformation $\dot{p}_a = L\dot{x}_1$, its derivative $\ddot{p}_a = \dot{L}\dot{x}_1 + L\ddot{x}_1$ and the property $J_cL = L^TJ_c^T = 0$, the following reduced model formulation is obtained for the constrained free-floating space manipulator

$$\bar{M}_{ef}\ddot{x}_1 + \bar{C}_{ef}\dot{x}_1 + \bar{E}_u = L^T\bar{J}_{aa}\tau + L^TJ_c^T\lambda + L^T\omega_x, \tag{8}$$

where

$$\begin{aligned}
&\bar{M}_{ef} = L^TM_{ef_{aa}}L,\\
&\bar{C}_{ef} = L^T(C_{ef_{aa}}L + M_{ef_{aa}}\dot{L}) = L^TC^L_{ef_{aa}},\\
&\bar{E}_u = L^T(M_{ef_{au}}\ddot{p}_u + C_{ef_{au}}\dot{p}_u) = L^TE_u,\\
&\omega_x = \bar{J}_{aa}\omega_{\tau_a}.
\end{aligned}$$

Observe that, also here, a premultiplication by a the factor L^T was employed so that the reduced model dynamics maintains the necessary structure and properties for controller formulation. Thus, $\bar{M}_{ef}$ is symmetric positive definite and $\bar{N}_{ef} = \dot{\bar{M}}_{ef} - 2\bar{C}_{ef}$ is skew-symmetric.

Let $p_a^d \in \mathbb{R}^n$ and $\dot{p}_a^d \in \mathbb{R}^n$ be the desired reference trajectory and the corresponding velocity for the end-effector controlled variables, respectively. Assume that p_a^d and its derivatives $\dot{p}_a^d$ and $\ddot{p}_a{}^d$ are bounded and belong entirely to the path independent workspace (PIW) [17], and therefore, $(p_a^d, \dot{p}_a^d, \ddot{p}_a{}^d)$ will not conduce to any dynamic singularity, i.e., $det(J) \neq 0$ throughout the proposed task. Define a bounded $f^d \in \mathbb{R}^n$ as the desired reference contact force. To be consistent with the imposed restrictions, assure that $\phi(p_a^d) = 0$ and $f^d = J_c^T(p_a^d)\lambda^d$.

Since $x_2 = \sigma(x_1)$, it is only necessary to find a control law that makes $x_1 \to x_1^d$ when $t \to \infty$. Therefore, define the position tracking error $\tilde{s}_1$ and the filtered link tracking error $\tilde{s}_2$ as

$$\tilde{s} = \begin{bmatrix} \tilde{s}_1 \\ \tilde{s}_2 \end{bmatrix} = \begin{bmatrix} x_1 - x_1^d \\ \dot{x}_1 - \dot{x}_1^d + p(x_1 - x_1^d) \end{bmatrix}, \tag{9}$$

for some constant $p > 0$. The error dynamic equations are given by

$$\dot{\tilde{s}} = \begin{bmatrix} \dot{\tilde{s}}_1 \\ \dot{\tilde{s}}_2 \end{bmatrix} = A\tilde{s} + Bu + B\omega, \tag{10}$$

where

$$A = \begin{bmatrix} -pI & I \\ 0 & -\bar{M}_{ef}^{-1}\bar{C}_{ef} \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ -\bar{M}_{ef}^{-1}L^T \end{bmatrix}$$

$$u = F_a + E_u - \bar{J}_{aa}\tau, \quad \omega = \omega_x, \quad \text{and} \quad F_a = M_{ef_{aa}}L(\ddot{x}_1^d - p\dot{\tilde{s}}_1) + C^L_{ef_{aa}}(\dot{x}_1^d - p\tilde{s}_1).$$

3. ADAPTIVE ROBUST CONTROLLER

Define a set of n neural networks $H_k(x_e, \Theta_k)$, $k = 1, \cdots, n$, where x_e is the input vector and Θ_k are the adjustable weights in the output layers. The single-output neural networks are of the form

$$H_k(x_e, \Theta_k) = \sum_{i=1}^{p_k} \theta_{ki} G\left(\sum_{j=1}^{q_k} w_{ij}^k x_{ej} + b_i^k\right) = \xi_k^T\Theta_k \tag{11}$$

where q_k is the size of vector x_e and p_k is the number of neurons in the hidden layer. The weights w_{ij}^k and the biases b_i^k for $1 \leq i \leq p_k$, $1 \leq j \leq q_k$ and $1 \leq k \leq n$ are assumed to be constant and specified by the designer. Thus, the adjustment of neural networks is performed only by updating the vectors Θ_k. The activation function for the neurons in the hidden layer is chosen to be $G(.) = tanh(.)$. The complete neural network is denoted by

$$H(x_e,\Theta) = \begin{bmatrix} H_1(x_e,\Theta_1) \\ \vdots \\ H_n(x_e,\Theta_n) \end{bmatrix} = \begin{bmatrix} \xi_1^T & 0 & \dots & 0 \\ 0 & \xi_2^T & \vdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \xi_n^T \end{bmatrix} \begin{bmatrix} \Theta_1 \\ \Theta_2 \\ \vdots \\ \Theta_n \end{bmatrix} = \Xi\Theta. \tag{12}$$

Consider the term

$$\bar{H} = F_a + E_u + \omega_x$$

in (10) completely unknown regarding its structure and parameter values. The neural network defined in (11) is applied to learn the dynamic behavior of the robotic system:

$$\bar{H} \approx H(x_e,\Theta) = \Xi\Theta, \tag{13}$$

where the input vector x_e should be defined as

$$x_e = \begin{bmatrix} q^T & \dot{q}^T & p_a^T & \dot{p}^T & \ddot{p}_u^T & (p_a^d)^T & (\dot{p}_a^d)^T & (\ddot{p}_a^d)^T \end{bmatrix}^T.$$

However, the values of q_b, $\dot{q}_b$, $\dot{p}_u$ and $\ddot{p}_u$ would be necessary, but they are not easy to obtain in practice. Considering that a neural network based approach is usually used when it is not possible to supply all the variables values to the system model, we have defined the vector x_e as

$$x_e = \begin{bmatrix} q_m^T & \dot{q}_m^T & (p_a^d)^T & (\dot{p}_a^d)^T & (\ddot{p}_a^d)^T \end{bmatrix}^T, \tag{14}$$

avoiding the necessity of any data from the free-floating base or related to passive variables.

Consider the constraint region of parameter Θ to be defined as in [14, 18] by $\Omega_\theta \doteq \{\Theta| \ \ \Theta^T\Theta \le M_\theta, \ M_\theta > 0\}$, where M_θ is a positive constant specified by the designer. Defining the following optimization problem

$$\Theta^* = \arg \min_{\Theta\in\Omega_\Theta} \max_{\tilde{s}\in\Omega_{\tilde{s}}} \|H(x_e,\Theta^*) - \bar{H}\|_2,$$

the error equation (10) may be rewritten as

$$\begin{aligned} \dot{\tilde{s}} =& A\tilde{s} + B(F_a + E_u - \bar{J}_{aa}\tau + \omega_x + H(x_e,\Theta^*) - H(x_e,\Theta^*)) \\ =& A\tilde{s} + B(-\bar{J}_{aa}\tau + H(x_e,\Theta^*)) + B(F_a + E_u + \omega_x - H(x_e,\Theta^*)) \\ =& A\tilde{s} + B(-\bar{J}_{aa}\tau + H(x_e,\Theta^*)) + B(\bar{H} - H(x_e,\Theta^*)) \\ =& A\tilde{s} + Bu + B\omega \end{aligned} \tag{15}$$

with

$$u = -\bar{J}_{aa}\tau + H(x_e,\Theta^*), \tag{16}$$

$$\omega = \bar{H} - H(x_e,\Theta^*), \tag{17}$$

where ω refers to external disturbances and the estimation error from the neural networks.

Let $u = \bar{u}$ be the control law provided by the nonlinear $\mathscr{H}_\infty$ controller, then τ can be computed by

$$\tau = \bar{J}_{aa}^{-1}(H(x_e,\Theta^*) - \bar{u}). \tag{18}$$

Regarding the nonlinear $\mathscr{H}_\infty$ control solution proposed in [14, 18] for constrained systems, define $\bar{u} = u_P + u_F$ such that

$$u_P = k_0 T \tilde{s}_2, \tag{19}$$

$$u_F = J_c^T \lambda_c, \tag{20}$$

where u_P is the $\mathscr{H}_\infty$ control term for the position enforcement and u_F is the $\mathscr{H}_\infty$ control law for the force tracking procedure, with

$$T := \begin{bmatrix} I_{(n-m)} \\ 0_{m\times(n-m)} \end{bmatrix} \quad \text{and} \quad \lambda_c := \lambda^d - k_\lambda(\lambda - \lambda^d),$$

for some constant gain k_0 and $k_\lambda > 0$.

Thus, considering a similar stability analysis to that of [14, 19], the adaptive neural network nonlinear $\mathscr{H}_\infty$ control solution for the constrained free-floating space manipulator subject to parametric uncertainties and external disturbances is stated as follows.

Theorem 3.1 *Let $H(x_e, \Theta)$ be a set of n neural networks defined by (11) with x_e being a vector of available data defined by (14) and Θ being a vector of adjustable parameters. Given a desired disturbance attenuation level $\gamma > 0$ and matrices $Z = Z^T > 0, Q = Q^T > 0, P_0 = P_0^T > 0, Z_0 = Z_0^T > 0$, and $R = R^T < \gamma^2 I$, the following performance criterion*

$$\int_0^T \left(\|\tilde{s}\|_Q^2 + \|\bar{u}\|_R^2\right) dt \leq \|\tilde{s}(0)\|_{P_0}^2 + \|\tilde{\Theta}(0)\|_{Z_0}^2 + \gamma^2 \int_0^T \|\omega\|^2 dt, \tag{21}$$

where $\tilde{\Theta} = \Theta - \Theta^*$ denotes the neural parameter estimation error, is satisfied, for any bounded initial condition, if there exists a dynamic state feedback controller

$$\dot{\Theta} = \begin{cases} -Z^{-T}\Xi^T L\tilde{s}_2 & \text{if } \|\Theta\| < M_\theta \text{ or } (\|\Theta\| = M_\theta \text{ and } \tilde{s}_2^T L^T \Xi\Theta \geq 0) \\ -Z^{-T}\Xi^T L\tilde{s}_2 + Z^{-T}\frac{\tilde{s}_2^T L^T \Xi\Theta}{\|\Theta\|^2}\Theta & \text{if } \|\Theta\| = M_\theta \text{ and } \tilde{s}_2^T L^T \Xi\Theta < 0 \end{cases} \tag{22}$$

$$\tau = \bar{J}_{aa}^{-1}[\Xi\Theta - k_0 T\tilde{s}_2 - J_c^T \lambda_c]. \tag{23}$$

solution of the adaptive neural network nonlinear $\mathcal{H}_\infty$ control problem subject to (15).

4. RESULTS

For validation purpose, the proposed adaptive $\mathcal{H}_\infty$ control solution is applied to a free-floating, planar, two-link space manipulator system. The corresponding DEM is a fixed-base, three-link, planar manipulator whose first joint is configured as passive, that is, $q_m = [\begin{array}{cc} q_2 & q_3 \end{array}]^T$ are the active joints. Its structure is based on the fixed-base manipulator UARM (UnderActuated Robot Manipulator).

A constrained trajectory tracking task is defined for the space manipulator end-effector. The task-space positions $p_a = [\begin{array}{cc} x_{ef} & y_{ef} \end{array}]^T$ of the end-effector are chosen to be the controlled variables, while its orientation φ_{ef} is let free.

The constraint surface imposed to the robot end-effector is a segment of a straight line on the X-Y plane, $\phi(p_a) : \mathbb{R}^2 \to \mathbb{R}$, given by

$$\phi(p_a) = -y_{ef} - x_{ef} + x_{ef}(0) + y_{ef}(0) = 0,$$

with $J_c = [\begin{array}{cc} -1 & -1 \end{array}]$. Defining $x_1 = x_{ef}$ and $x_2 = y_{ef}$, we have $x_2 = \sigma(x_1) = -x_1 + x_{ef}(0) + y_{ef}(0)$ and, hence, $L(x_1) = [\begin{array}{cc} 1 & -1 \end{array}]$.

The reference position trajectory is defined at the constraint surface starting at the end-effector initial position. The sweep of the desired reference trajectory $x_1^d(t)$ follows a fifth degree polynomial with $t_f = 3s$ (time defined for the task execution). It is desired that the end-effector track the constraint surface without applying any force on the normal direction of the constraint line, so the desired reference force is defined $\lambda^d = 0$. During the simulation, a limited disturbance, initializing at $t = 1s$, was introduced in the form $\tau_d = \left[\begin{array}{c} 0.02e^{-2t}\sin(2\pi t) \\ 0.01e^{-2t}\sin(2\pi t) \end{array}\right]$. Multiplicative random uncertainties were also applied to the values of mass, inertia, length and position of center of mass as $\delta = [\begin{array}{cccc} 0.7*m & 1.2*I & 1.1*W & 0.8*l_c \end{array}]$.

The level of disturbance attenuation defined for the proposed nonlinear $\mathcal{H}_\infty$ controller is $\gamma = 2$. The selected gains are defined $p = 1.5$, $k_0 = 55$, $k_\lambda = 0.5$ and $Z = 1$. Let $n = 2$ be the size of p_a determined by the number of joints of the space manipulator (active joints in DEM), which define the size of x_e, $q_k = 10$. Define $H(x_e, \Theta) := [\begin{array}{cc} H_1(x_e, \Theta_1) & H_2(x_e, \Theta_2) \end{array}]^T$ with $p_k = 7$ neurons in the hidden layer, the bias vector $b_k = [\begin{array}{ccccccc} -3 & -2 & -1 & 0 & 1 & 2 & 3 \end{array}]$ and the weighting matrix for the first layer $\Omega_i^k = [\omega_{ij}^k] = [\begin{array}{cccccccccc} 1 & 1 & 1 & 1 & -1 & -1 & -1 & -1 & -1 & -1 \end{array}]$. Simulation results for the adaptive neural network nonlinear $\mathcal{H}_\infty$ controller are shown in Figures 2 and 3.

In order to clearly identify the controllers actuation, Figure 2 illustrates the results obtained without adding uncertainties and disturbances (nominal case) while Figure 3 shows the results for the disturbed situation (disturbed case). A green mark identifies, in Figure 3, the instant when the disturbance begins ($t = 1s$).

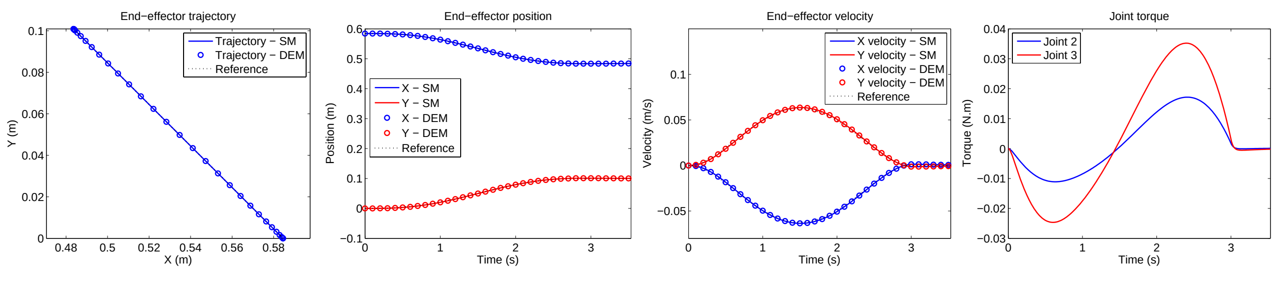

Figura 2: End-effector trajectory, end-effector position, end-effector velocities and applied torques - Nominal case.

By comparing Figures 2 and 3, the robustness characteristic of the applied $\mathcal{H}_\infty$ criterion can be verified. The graphical results illustrate that the applied controller reject disturbance efficiently and attenuate its effect in the trajectory tracking task. It can also be noted that the adaptive neural networks approach exhibits its efficiency in estimating the effect of uncertainties, and mainly,

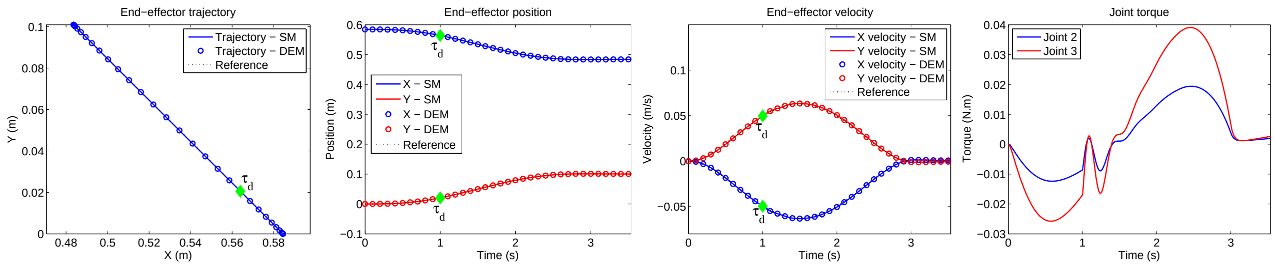

Figura 3: End-effector trajectory, end-effector position, end-effector velocities and applied torques - Disturbed case.

the unmodeled dynamics of the space manipulator. Considering the hostile environment where a space robot operates, which can deteriorate its structure and physical characteristics, and also considering the difficulty of taking the system back to reformulate its dynamic model due to these uncertainties, the results obtained by the proposed intelligent adaptive robust controller are very interesting.

5. CONCLUSION

The problem defined in this work concerns about controlling, simultaneously, the position of the end-effector of a free-floating base manipulator and the contact force exerted by it into a constraint surface, considering parametric uncertainties involved in the models of the robot and the constraint surface as well as the presence of external disturbances. A task-space based formulation was proposed to the problem. The adaptive design proposed apply an intelligent learning strategy to estimate uncertain parameters and also the behavior of unmodeled dynamics. The $\mathscr{H}_\infty$ control law is applied to attenuate the effects of estimation errors and external disturbances. The presented method does not demand measured values of acceleration neither from the free-floating base nor from the arm. Simulation results showed the effectiveness of the proposed control strategy for the considered application.

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