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Bond Graph Modeling And Sliding Mode Control For Musculoskeletal Human Arm

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***Abstract*—In this paper, we consider a controlled robotic system that replace the musculoskeletal human arm system in the case of spinal cord damage. First, the system is modeled using Bond graph method and 20-sim software. Second, a control law based on the sliding mode control is designed to underline the efficiency of the method to assure the tracking trajectories. Finally, implementation of the control scheme on MATLAB and simulation results are demonstrated.**

Keywords—musculoskeletal; bond graph modeling; sliding mode control; tracking trajectory.

I. INTRODUCTION

The scientific development of electronics, computer science and mainly control system engineering lead to the progress of robotics technologies, currents robots are able to replace the human intervention in different domains like medical [1], industries [2], space [3] and haptics [4]. We are especially interested in a robotic system that substitute the role of spinal cord and replace the disabled nerves between brain and muscles in case of accident or disease.

Several research works proposed a dynamic model for the human arm model shown in figure1. The main objective is to elaborate the adequate force that enable the arm to follow the desired trajectory. Sensory control [5], model predictive control [6] and adaptive control [7] were proposed to pursuit the desired setpoint using a musculoskeletal model.

In this work, the modelling of the human arm is simplified to a manipulator with two degree of freedom, the dynamic model is obtained using the bond graph language. It is a graphical method based on the interaction (cause-effect) between the components of the system [8]. It is a powerful technique used for several mechanical or electrical systems that avoid the complexity of other methods like Lagrange or Newton-Euler [9]. Besides, the dynamic equations can be easily generated using software like 20-sim or symbos.

The second step is to design the controller for this nonlinear system to perform the trajectory tracking.

The sliding mode control (SMC) approach has proven its advantages in terms of high-speed response, robustness to parameter uncertainties and external disturbances [10]. The design of SMC consists of two stages. The first one is to constrain the trajectories of the system to reach the sliding surface and the second one is to force the states of the system to remain there [11]. However, these performances come at the cost of high frequency switching of the control input causing what called chattering phenomenon. To bound this problem, we propose the use of hyperbolic function instead of sign function in the discrete term of the control law [12, 13].

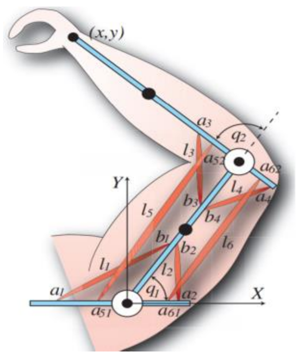

Fig. 1.*Two links planar arm model*

II.BOND GRAPH MODELING

Bond graph modelling is used to simulate multibody mechanical systems and applied to manipulator with two degree of freedom that simulate the elbow and shoulder joint movements. The model consists of two links that represents the upper arm (link1) and the forearm (link2). So, the system can be simplified as in figure 1. The basic element of bond graph is the power bond (figure 2) that represents the effort and the flow. The meaning of these two variables depends on the physical domain presented by the bond as shown in the figure 2.

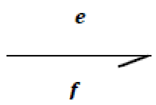

Fig. 2.*Energy bond*

To calculate the dynamic model, let's define the vector of generalized coordinates $q = [q_1 \quad q_2]^T = [\theta_1 \quad \theta_2]^T$, where θ_1 and θ_2 represent the joint angles of link1 and link2 respectively. Let a_1 and a_2 be the links lengths, l_1 and l_2 the distances of the centres of mass of the two links from the respective joint axes. Also let m_{l_1} and m_{l_2} be the masses of the two links, and finally, I_{l1} and I_{l1} the moments of inertia of to the centres of mass of the two links.

TABLE I. EFFORT AND FLOW VARIABLES IN SOME PHYSICAL DOMAINS

Domain	Effort (e)	Flow (f)
Translation Mechanics	Force	Velocity
Rotational Mechanics	Torque	Angular Velocity
Electricity	Voltage	Current

The components of bond graph are classified by their energetic behavior to passive elements R relative to energy dissipation, I and C relative to energy storage and active elements S that represents the energy source. These components describe the relation between effort and flow of each element of the graph. These elements are connected through two types of junctions: junction zero (common effort junction) and junction one (common flow junction). Finally, to simplify the construction of the bond graph, we follow the approach of Karnopp and Rosenberg [14] that consists on some steps:

Junction 1 is associated to each component of the kinematic vectors $\dot{q}$ and $\dot{q}_I$, then other junction composed of transformers and junction 0 are constructed reporting kinematic relationships written above. Finally, the elements I, C, R and the sources corresponding to the phenomena taken into account in the system modelling assumptions are added. So, we get the model in the figure 3. The key vectors q, q_I and q_C are respectively related to the generalized coordinates, the inertial energy storage (positions of moving masses and inertias) and potential type energy storage (elongation of stretched or compressed springs).

$$q_I = \begin{bmatrix} \theta_1 \\ x_{G1} \\ y_{G1} \\ x_{G2} \\ x_{G2} \\ \theta_2 \end{bmatrix}, \mathrm{q_C} = 0, \dot{q}_I = \begin{bmatrix} \omega_1 \\ -l_1 sin(\theta_1)\dot{\theta}_1 \\ l_1 cos(\theta_1)\dot{\theta}_1 \\ -a_1 sin(\theta_1)\dot{\theta}_1 - l_2 sin(\theta_1+\theta_2)(\dot{\theta}_1+\dot{\theta}_2) \\ -a_1 sin(\theta_1)\dot{\theta}_1 - l_2 cos(\theta_1+\theta_2)(\dot{\theta}_2+\dot{\theta}_2) \\ \omega_2 \end{bmatrix}$$

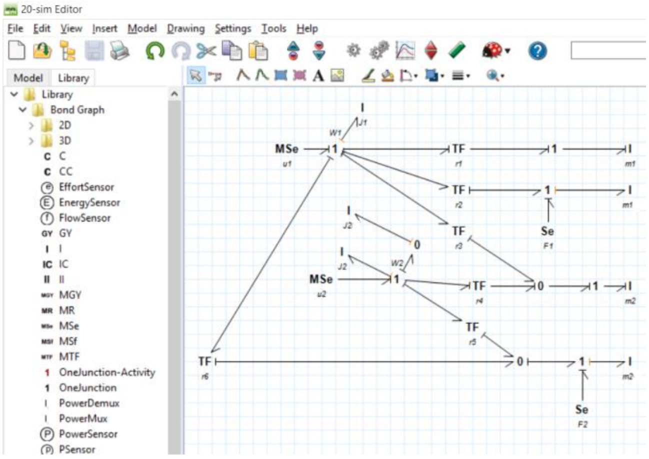

Fig. 3.*The bond graph model of the manipulator with 20-sim software*

MSe: Modulated effort sources that represents the control input applied to joints.

TF: Ideal transformer that represents a power continuous relation between the efforts and flows of both its ports.

Se: Effort source that represent the gravitational forces applied to both joints.

From the bond graph model implemented in 20-sim (figure 3), we obtain a set of manipulator robot differential equations summarized in the following matrix form:

$$M\ddot{\theta} + N\dot{\theta} + G = U \quad (1)$$

$$\begin{bmatrix} M_{11} & M_{12} \\ M_{12} & M_{22} \end{bmatrix}\begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix} + \begin{bmatrix} -F_{12}\dot{\theta}_2 & -F_{12}(\dot{\theta}_{1+}\dot{\theta}_2) \\ F_{12}\dot{\theta}_1 & 0 \end{bmatrix}\begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} + \begin{bmatrix} G_1 g \\ G_2 g \end{bmatrix} = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \quad (2)$$

where the elements of the inertia matrix M are given by:

$$M_{11} = I_{l1} + I_{l2} + m_{l_1} l_1^2 + m_{l_2} l_2^2 + m_{l_2} a_1^2 + 2m_{l_2} a_1 \, l_2 \cos(\theta_2)$$

(2.1)

$$M_{12} = I_{l2} + m_{l_2} l_2^2 + m_{l_2} a_1 \, l_2 \cos(\theta_2) \quad (2.2)$$

$$M_{22} = 2I_{l2} + m_{l_2} l_2^2 \quad (2.3)$$

$$F_{12} = -m_{l_2} a_1 \, l_2 \, s\,in(\theta_2) \quad (2.4)$$

$$G_1 = (m_{l_1} + m_{l_2}) l_1 \cos(\theta_1) + m_{l_2} \, l_2 \cos(\theta_1 + \theta_2)$$

(2.5)

$$G_2 = m_{l_2} \, l_2 \cos(\theta_1 + \theta_2) \quad (2.6)$$

III. SLIDING MODE CONTROL DESIGN

Sliding mode control is a variable structure control that can change structure and commute between two values in a specific switching logic $s(x)$ where x is the state of the system. The principle of sliding mode control is to force the system to reach a given surface called the sliding surface and to remain there until it reaches equilibrium [15]. This command is done in two steps: the convergence towards the surface and then the sliding along it. The synthesis of the sliding mode control is done in three steps: - choice of the sliding surface - Establish the condition of convergence - determine the control law that allows to reach the surface and stay there.

A. Design of Sliding Mode Controller based on switch function

To control the joint positions θ_1 and θ_2 of the manipulator, two sliding surfaces are chosen as follow:

$s_i = \dot{e}_i + \lambda_i e_i, \lambda_i > 0\, , i = 1,2.$ (3)

where e_i represents the joint angles errors such as:

$e_i = \theta_i^d - \theta_{i\,,} i = 1,2$ (4)

and θ_i^d is the desired position of the i^{th} joint angle.

The sliding mode controller u consists of two terms: the equivalent control part u_e that maintain the system states on the sliding surface and a switching control part u_s that ensure the convergence of the system to the sliding manifold $s = 0$. Then we have:

$U = U_e + U_s$(5)

From $\dot{s} = 0\, , i = 1, 2$, we conclude the equivalent control part u_e. So, we have:

$U_e = M[\lambda\dot{e} + \ddot{q}_d] + N + G$ (6)

Such as

$\lambda = \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix}$, $\varepsilon = \begin{bmatrix} \varepsilon_1 & 0 \\ 0 & \varepsilon_2 \end{bmatrix}$, $k = \begin{bmatrix} k_1 & 0 \\ 0 & k_2 \end{bmatrix}$, $S = [s_1 \quad s_2]^T$,

For the reaching law using sign function we have:

$\dot{s} = -k\; sign(s) + \varepsilon\; s$ (7)

Then the switching control term is expressed as:

$U_s = M[k\; sign(s) + \varepsilon\; S]$ (8)

We obtain the overall control law:

$U = M(q)[k\; sign(s) + \varepsilon\; s + \lambda\dot{e} + \ddot{q}_d] + N\; \dot{q} + G$ (9)

B. Design of Sliding Mode Controller based on tanh function

For the reaching law using the hyperbolic tangent function we have this expression:

$\dot{s} = -k\; tanh(s) + \varepsilon\; s$ (10)

then the switching control term is expressed as:

$u_s = M[k\; tanh(s) + \varepsilon\; s]$ (11)

The control law is such as:

$U = M(q)[k\; tanh(s) + \varepsilon\; s + \lambda\dot{e} + \ddot{q}_d] + N(q, \dot{q})\dot{q} + G(q)]$(12)

IV. SIMUMATION RESULTS AND DISCUSSION

SMC controller and manipulator system were introduced in MATLAB as shown in figure 4. Let the initial states of the plant set as $q_0 = [\theta_{10} \quad \theta_{20}]^T = [-1.4 \quad -1.4]^T$, and the setpoint set as $\theta_{1d} = \theta_{2d} = \sin(t)$.

$\lambda_1 = 5, \lambda_2 = 7$, $\varepsilon_1 = 10$, $\varepsilon_2 = 12$, $k_1 = 0.3$, $k_2 = 0.2$,

$m_1 = 0.5\, Kg$, $m_2 = 0.4\, Kg$, $l_1 = 0.5\, m$, $l_2 = 0.4\, m$.

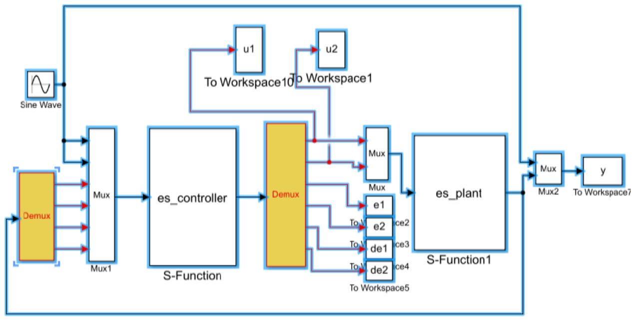

Fig. 4.*System and controller design with Simulink*

For the sign function, the control inputs are shown in figures 5 and 6. The control Input signals include high speed oscillation and demonstrate the chattering phenomenon. Figures 7 and 8 represent the control inputs applied to joint1 and joint2 using the tanh function to perform the tracking of the setpoint. We note an attenuation of the oscillation, and the control signals are more smoothed by substituting the switch function with tanh.

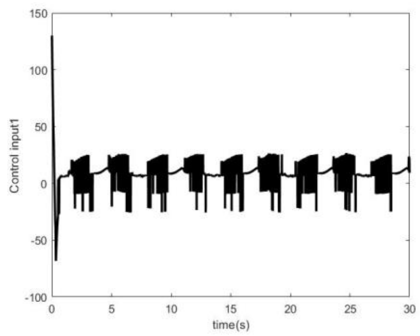

Fig. 5.*Control input $u_1$using sign function*

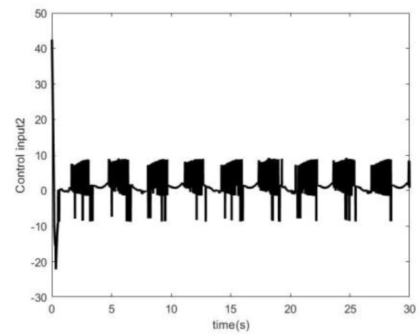

Fig. 6.*Control input $u_2$using sign function*

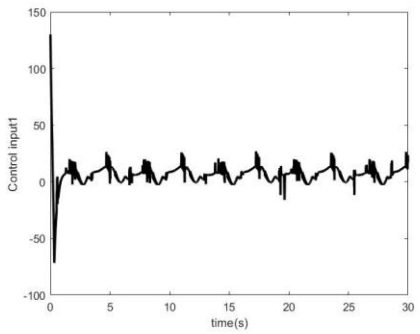

Fig. 7.*Control input $u_2$using sign function*

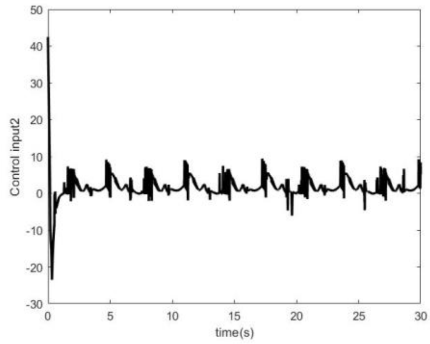

Fig. 8.*Control input $u_2$using sign function*

In both cases, figures 9 and 10 illustrate good performances of the tracking control and the system reach the desired position or speed trajectory in a short time by applying the SMC controller.

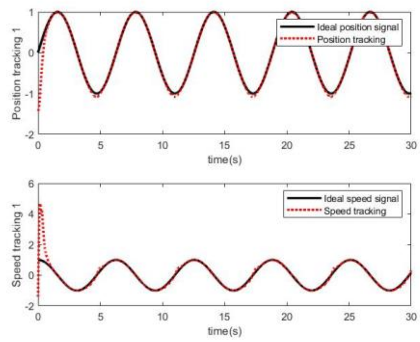

Fig. 9.*Angular position and speed responses for joint1*

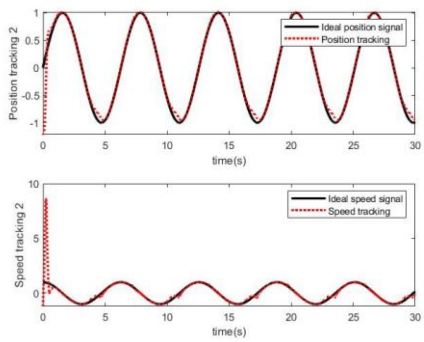

Fig. 10.*Angular* position and speed responses for joint2

V.CONCLUSION:

This work demonstrates the advantages of bond graph approach in term of simplicity and efficiency. It's used to extract the dynamic model of a polyarticular system that control the musculoskeletal human arm. Then, an SMC controller is designed to perform the tracking control of the setpoint. The advantages of this control technique are proved in the simulation results and the chattering of the applied torque was smoothed using the hyperbolic tangent function to minimize the discontinuity. However, the choice of the control law parameter like λ, ε and k is sensitive and have to be adjusted with the setpoint or in presence of disturbances

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