

Hybrid Position/Force Controller Applied to Exoskeleton

Z. Achour and M. Hamerlain

Abstract—Exoskeleton robots was designed to be worn on the lateral side of an upper extremity and is able to assist arm movements The approach hybrid force-position for controlling compliant motions of exoskeleton is presented in hybrid technique described combines force with positional data to satisfy simultaneous position and force trajectory, Some simulations are presented that verify the performance of the controller for different situations.

Index Terms—Hybrid position/force control, exoskeleton robot, nonlinear system.

I. INTRODUCTION

This paper presents an upper extremity (UE) with five degrees of freedom rotoid joint wearable robot and its control strategy to provide movement assistance and active rehabilitation exercises to physically disabled individuals, For the exoskeleton can work correctly and thus achieve the expected results in terms of rehabilitation or assistance, it must be strictly controlled, a position controller alone generally gives poor performance and may even cause instability. Hybrid position / force control is required [1]-[3]. This paper presents an external hybrid force/position controller for an exoskeleton robot using a cascade scheme with two control loops. In the outer loop there is a force controller that acts as a perturbation for the position reference, the inner loop, which is used to control the end-effector position, uses both the signals generated by the outer loop and the desired end-effector position. The control laws are simple, the PID type for joint servoing and PI for the external force loop. The mechanical structure of the exoskeleton is a closed chain, the dynamic modeling of robots is an important for simulation and control of robots different technique have been proposed [4], [5].in this paper we use Newton-Euler (NE algorithm) recursive technique .

This paper is organized as follows: dynamic model in Section 2, different methods Hybrid Position/Force Controller in section 3, simulation results are presented and discussed in section 4, conclusions and outlook on future work are given in section 5

II. DYNAMIC MODEL

Our exoskeleton is a multi-contact system with five

Manuscript received November 26, 2018; revised December 22, 2018. This work is supported by the Centre for the Development of Advanced Technologies of Algiers (CDTA), Algeria.

Z. Achour is with the Centre for the Development of Advanced Technologies, Cité 20 août 1956, BP. N° 17, Baba Hassen 16303, Algiers, Algeria (tel: +213 21 35 10 18, e-mail: zachour@cdta.dz).

M. Hamerlain is with the Centre for the Development of Advanced Technologies, Cité 20 août 1956, BP. N° 17, Baba Hassen 16303, Algiers, Algeria (e-mail: mhamerlain@cdta.dz).

degrees of freedom. It includes 08 joints with 07 bodies attached to a base. Five of the 08 joints are active by DC motors, and the other joints are passive.

$$\begin{cases} \mathbf{q} = \begin{bmatrix} q_{tr} \\ q_c \end{bmatrix} \\ q_{tr} = [q_1 \ q_2 \ q_3 \ q_4 \ q_5 \ q_6 \ q_7] \\ q_c = [q_8] \end{cases} \quad (1)$$

$$q_a = [q_1 \ q_3 \ q_4 \ q_5 \ q_6] \quad (2)$$

$$q_p = \begin{bmatrix} q_2 \\ q_7 \end{bmatrix} \quad (3)$$

where

- q_{tr} Vector of the tree structure joint variables
- q_c Vector of the cut joints
- q_a and q_p are respectively vectors of active joint and the passive joint

Inverse Dynamics Using Recursive NE Algorithm

The Newton-Euler equation giving the external forces and moments on a link j about the origin frame j is written as:

$$\Gamma = NE(\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}}, \mathbf{f}_e, \mathbf{m}_e) \quad (4)$$

where:

- \mathbf{q} , $\dot{\mathbf{q}}$ and $\ddot{\mathbf{q}}$ are respectively, the position, velocity and acceleration of the robot .
- \mathbf{f}_e and \mathbf{m}_e are the external forces and moments of the links of the robot on the environment

The forward algorithm is given for $j=1, \dots, n$ with $i=a(j)$ as follows:

$$\omega_1^j = R_1^j \omega_1^i \quad (5)$$

$$\omega_j^j = \omega_i^j + \bar{\sigma}_j a_j^j \quad (6)$$

$$\dot{\omega}_j^j = R_i^j \dot{\omega}_i^j + \bar{\sigma}_j (\ddot{q}_j a_j^j + \omega_i^j \times \dot{q}_j a_j^j) \quad (7)$$

$$\dot{V}_j^j = R_i^j (\dot{V}_i^j + U_i^j P_j^i) + \sigma_j (\ddot{q}_j a_j^j + 2\omega_i^j \times \dot{q}_j a_j^j) \quad (8)$$

$$F_j^j = M_j V_j^j + U_j^j M S_j^j \quad (9)$$

$$M_j^j = J_j^j \dot{\omega}_j^j + \omega_j^j \times (J_j^j \omega_j^j) + M S_j^j \times \dot{V}_j^j \quad (10)$$

These equation are initialized by $\omega_0 = 0, \dot{\omega}_0 = 0, \dot{V}_0 = -g, U_0^0 = 0$, with g is the acceleration of gravity.

Where

$$q_j = \bar{\sigma}_j \theta_j + \sigma_j r_j \quad (11)$$

where $\sigma_j = 0$ if joint j is revolute, $\sigma_j = 1$ if joint j is prismatic, and $\bar{\sigma}_j = 1 - \sigma_j$

T_i^j is the screw transformation matrix given as

$$T_i^j = \begin{bmatrix} R_i^j & -R_i^j \hat{P}_j^i \\ 0_{3 \times 3} & R_i^j \end{bmatrix} \quad (12)$$

where R_i^j Rotation matrix from i to j

- ω_j the angular velocity of link j
- \dot{V}_j the linear acceleration of the origin of frame j
- F_j total external forces on link j
- M_j total external forces on link j about O_j
- J_j (6x6) inertia matrix of link j

$$J_i^j = \begin{bmatrix} M_j I_3 & -M \hat{S}_j^j \\ M \hat{S}_j^j & J_j^j \end{bmatrix} \quad (13)$$

where M_j , MS_j and J_j are the standard inertial parameters of link j . They are respectively, the mass, the first moments, and the inertia matrix about the origin. With

$$U_j^j = \hat{\omega} + \hat{\omega}_j^j \hat{\omega}_j^j \quad (14)$$

And where a_j is the unit vector along the z_j axis which is the axis of joint j .

The matrix \hat{W} defines the 3×3 vector product matrix associated to the (3×1) vector W such that :

$$\hat{W} = \begin{bmatrix} 0 & -w_z & w_y \\ w_z & 0 & -w_x \\ -w_y & w_x & 0 \end{bmatrix} \quad (15)$$

$$W \times V = \hat{W}V$$

The backward equation can be calculated for $j=1, \dots, n$:

$$f_j^j = F_j^j + f_{ej}^j \quad (16)$$

$$m_j^j = M_j^j + m_{ej}^j \quad (17)$$

$$f_j^i = R_i^j f_j^j \quad (18)$$

$$f_{ei}^i = f_{ei}^i + f_j^i \quad (19)$$

$$m_{ei}^i = m_{ei}^i + R_i^j m_j^j + P_j^i \times f_j^i \quad (20)$$

$$\Gamma = (\sigma_j f_j^j + \bar{\sigma}_j m_j^j)^T a_j^j + I_{a_j} \ddot{q}_j + F_{s_j} \text{sign}(\dot{q}_j) + F_{v_j} \dot{q}_j \quad (21)$$

where f_j and m_j are the reaction forces and moments of link $a(j)$ on link j respectively, I_{a_j} is the inertia of the rotor transmission gears of the motors of joint j , F_{s_j} and F_{v_j} are the coulomb and viscous friction parameters respectively, f_{ej}^j and m_{ej}^j are the external force and moments of link j on the

environment.

III. HYBRID CONTROL

W Khaliland E.dombre distinguished [6] in two types of hybrid force/position control:



Fig. 1. Exoskeleton.

A. Parallel Hybrid Force-Position Control

The basic approach for the hybrid force-position control was already presented by Raibert and Craig (1981) [7], [8]. The control problem is divided into parallel control loops for position and force control with their set-point X_{set} and F_{set} respectively with the selection matrix S , the N degrees of freedom (DOF) are assigned to be either force or position controlled (See Fig. 1)

$$\Gamma_i = \sum_{j=1}^N \{ \Gamma_{ij} [s_j \Delta f_j] + \psi_{ij} [(1 - s_j) \Delta x_j] \} \quad (22)$$

where :

- Γ_i is torque applied by the i_{th} actuator
- Δf_j is force error in j_{th} DOF
- Δx_j is the position error in j_{th} DOF
- Γ_{ij} and ψ_{ij} are force and position compensation functions, respectively, for the j_{th} input and this i_{th} output
- s_j component of compliance selection vector :

$$s = \text{diag}(s_1, s_2, s_3, \dots, s_N)$$

with

$s_j=0$ If the j_{th} DOF is controlled in position

$s_j=1$ If the j_{th} DOF is controlled in force

W. Khalil et E. Dombre distinguishes three control diagram control:

- Control diagram of hybrid position and force proposed by Raibert And Craig (1981)

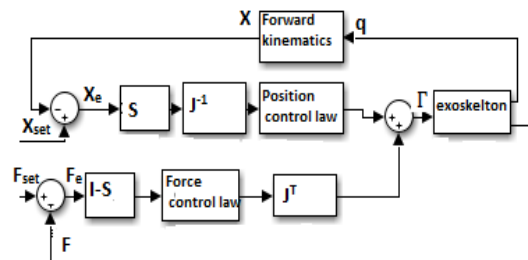


Fig. 2. Control diagram of hybrid position and force proposed by Raibert And Craig (1981).

- Control diagram of hybrid force-position control with sum of velocity

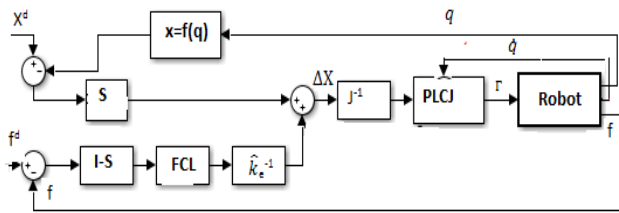


Fig. 3. Control diagram of hybrid force-position control with sum of velocity.

where:

PCLJ position control law in the joint space

FCL force control law

\hat{k}_e^{-1} Estimated stiffness matrix

- Control diagram of hybrid force-position control with sum of efforts

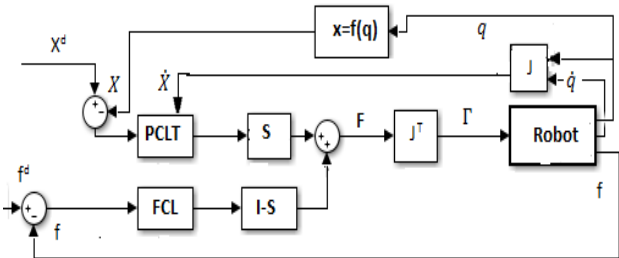


Fig. 4. Control diagram of hybrid force-position control with sum of efforts.

B. External Hybrid Force-Position Control

External Hybrid Control scheme below (Fig. 2) gives an overview of the representation of a hybrid control qset (5x1) and Fset (6x1) inputs for the respective position desired and force desired. The position loop runs independently when there are no forces acting on the tool tip. Once forces are sensed, a force error is generated based on the force constraints set [9], [6], [10]. A corrective position term is then added to the output from the position loop.

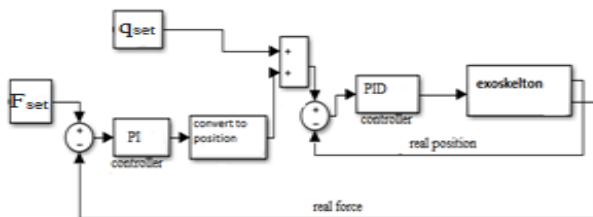


Fig. 5. External hybrid control scheme.

IV. RESULTS

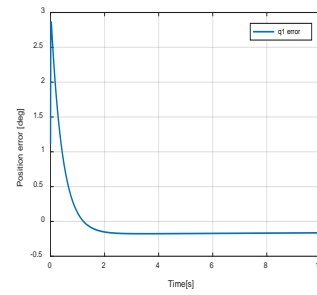
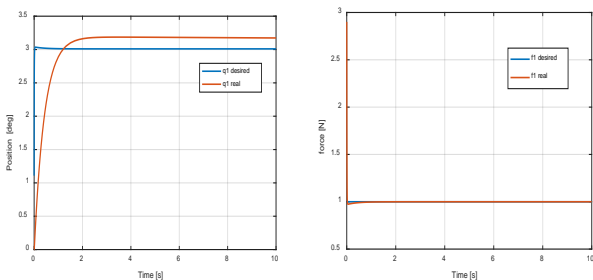


Fig. 6. Responses of position, force and position error respectively of axis1.

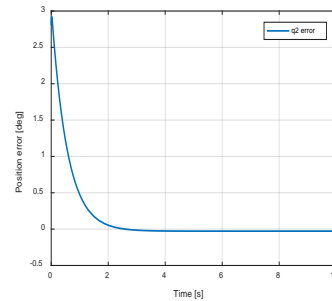
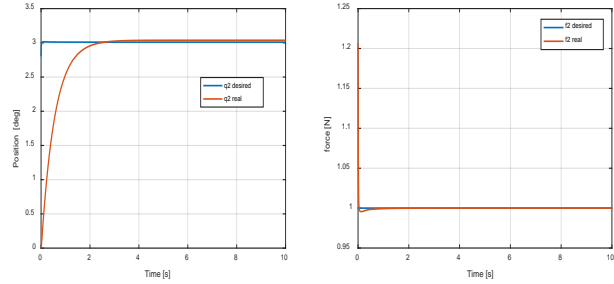


Fig. 7. Responses of position, force and position error respectively of axis2.

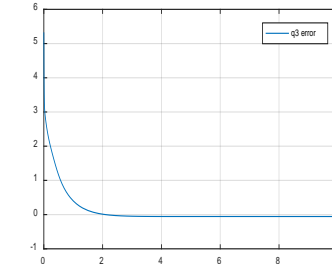
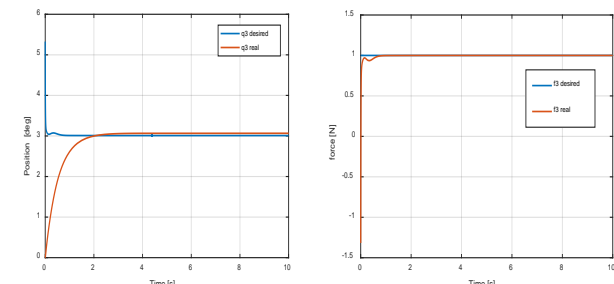
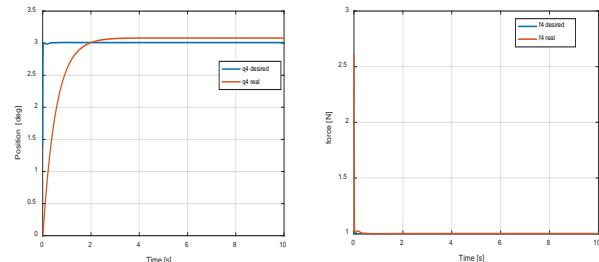


Fig. 8. Responses of position, force and position error respectively of axis3.



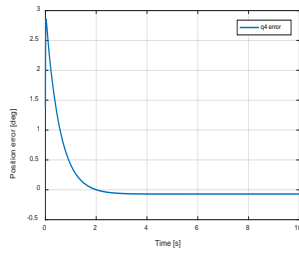


Fig. 9. Responses of position, force and position error respectively of axis4.

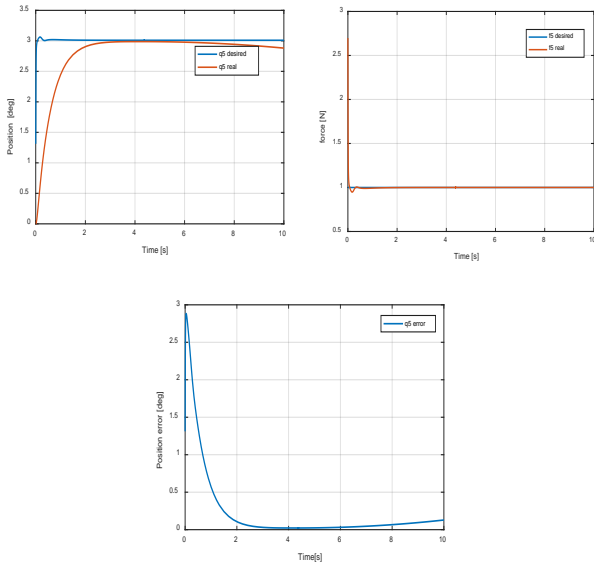


Fig. 10. Responses of position, force and position error respectively of axis5.

From the result presented it can be seen that the desired position given for the exoskeleton is good, The error in position, at the same pace as the force setting, which confirms that the variation in the position is due mainly to the variation in the force setting.

V. CONCLUSION

In this paper, first we model our exoskeleton by identification, after this step we propose different methods Hybrid Position / Force Controller, Parallel hybrid force-position control External Hybrid diagram control

Controllers PID to be implemented on our robot, simulation results are satisfying several perspectives of improvement are envisaged in the future from its implementation of External Hybrid Control on our exoskeleton.

REFERENCES

- [1] M. H. Raibert and J. J. Craig, "Hybrid Position/Force Control of Manipulators," *Journal of Dynamic Systems, Measurement, and Control*, vol. 103, no. 4, pp. 126-133, 2009.
- [2] D. Nganga-Kouya1 and F. A. Okou, "Méthodologie hybride de conception de la commande force/position des robots manipulateurs," *Afrique Science*, vol. 5, no. 3, pp. 111-127, 2009.
- [3] W. Khalil, "Dynamic modeling of robots using recursive Newton-Euler techniques," in *Proc. of 7th International Conference on Informatics in Control, Automation and Robotics (ICINCO 2010)*, 2010.
- [4] K. Blokkum, "Design and analysis of a hybrid position/force controller for robotic rehabilitation of upper limb after stroke," M.S. thesis, Norwegian University of Science and Technology, Trondheim, Norway, 2016.
- [5] P. Letier, "Bras exosquelette haptique: Conception et contrôle," Ph.D. thesis, Université libre de Bruxelles, Brussels, Belgium, 2010.
- [6] W. Krauss, P. Miermeister, V. Schmidh, and A. Pott, "Hybrid position-force control of a cable-driven parallel robot with experimental evaluation," *Journal of Mechanical Science*, pp.119-125, 2015.
- [7] K. Anam and A. AL-Jumaily, "Active exoskeleton control systems: State of the art," *Procedia Engineering*, vol. 41, pp. 988-994, 2012.
- [8] Z. Y. Yang, Y. G. Zhu, X. X. Yang, and Y. S. Zhang, "Impedance control of exoskeleton suit based on adaptive RBF neural network," in *Proc. of the International Conference on Intelligent Human-Machine Systems and Cybernetics (IHMC 2009)*, pp. 182-187, 2009.
- [9] W. Yu and J. Rosen, "A novel linear PID controller for an upper limb exoskeleton," presented at the 49th IEEE Conference on Decision and Control (CDC), 2010.
- [10] W. Khalil and E. Dombre, *Modeling, Identification and Control of Robots*, London: Hermes Penton Science, 2005, p. 500.



systems and robust control of nonlinear robotic systems.

Zina Achour received engineering in electronics option control from the Algerian University of Science and Technology Houari Boumediene (USTHB). In 2011, she obtained Master degree in electronics at USTHB. Since March 2007, she was employed as a Research Engineer in Robotics Laboratory at Advanced Technologies Development Center (CDTA), Algeria. Her research interests include, modeling of dynamic



Hamerlain Mustapha is a Research Director. He received the doctorate degree in 1993 from National Institute of Applied Sciences of Toulouse (France). He is a researcher in the robotics department of the Advanced Technologies and Development Center (CDTA) of Algiers and professor at the school (EMP). From 1988 to 1993, he was involved in a research project in the field of robotics PAM (Pneumatic Artificial Muscles) as a researcher at the National Institute of Applied Sciences (INSA) of Toulouse. His current research interests include robust control of nonlinear systems, robot motion control, visual control, robots manipulators and pneumatic artificial muscles actuators.