An Experimental Study on the 7-DOF ANAT Robot using Hierarchical Control Strategy

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Abstract— **This paper presents a new hierarchical control strategy for a hyper redundant articulated nimble adaptable trunk (ANAT). This control strategy is used to track a workspace trajectory using a feedback linearization approach. The hierarchical control strategy consists in controlling the last joint by assuming that the remaining joints follow their desired trajectories. The same strategy is applied backward to control the (n-1)-th joint, and so on until the first joint. The pseudo-inverse of the Jacobian is used to solve the inverse kinematics problem and the local stability of each step is proved. This algorithm is experimented on a seven DOF ANAT robot and gives effective results and good tracking of a desired workspace trajectory in rectangular form.**

I. Introduction

Nonlinear systems have been the focus of attention of several studies. With their nonlinear dynamics, robot manipulators are good candidates and a challenging control problem. In robotics, the workspace control figures prominently and is more interesting than joint space control. In fact, the tasks, such as painting, assembly etc., are usually performed by the end effectors in the robots workspace. For the workspace control, many robot manipulators are used such as redundant robot, for which the dimension of the joint space position vector is greater than the dimension of its workspace vector. In this case the inverse kinematics problem has an infinite number of solutions. Much effort for the inverse kinematics problem of redundant robots was devoted in [1, 2].

Many control schemes are used in the literature for solving robot manipulators control problem. The Feedback linearization approach was used in [3-6] to solve the tracking control problem for robot manipulators. In [6] the feedback linearization is used when the decoupling matrix is non-square such as in the redundant robots case. For the workspace control of redundant robots, a partial feedback linearization approach was used in [3] for a triangular form of the modified dynamics. A PPR redundant robot is used as a case study and an algorithm based on feedback linearization was proposed to compute the end-effector commands that produce the desired reconfiguration in finite time.

When the robot dynamics is viewed as interconnected subsystems, decentralized control can be used to control robot manipulators [7-11]. A discrete-time decentralized control scheme was proposed in [8] for five DOF robot to track a desired trajectory in the joint space. The neuronal network and a backstepping approach are used to develop a decentralized control law. A design method for a decentralized control of manipulators is proposed in [9]. The model dynamic is represented as a set of interconnected subsystems and their dynamics are divided into two parts: a nominal system and uncertainties. Riccati equation and decentralized control strategy are used for control design.

When the system's parameters are unknown, adaptive control [1, 12-15] is used for solving robot manipulators control problem. An adaptive control scheme for redundant variable geometry truss manipulators based on a fuzzy neural network is proposed in [14]. For the identification problem of the inverse dynamics model, a fuzzy neural network model and an adaptive workspace tracking controller were used. A feedback linearization approach and least square estimation are used to develop the control law. The sliding mode approach with adaptive control were merged in [16] to control robot manipulators using classical sliding surface. A novel approach was proposed in [17] to reduce the chattering. The proposed reaching law has an exponential term that is a function of the sliding surface.

Intelligent control methods were also used for robot manipulators control problem [8, 18-20]. A decentralized adaptive fuzzy control scheme was proposed in [19] for reconfigurable manipulator to satisfy the concept of modular software. Two adaptive neuro-fuzzy control structures are applied for a 2-DOF planar manipulator in [20].

Several nonlinear control schemes were used for robot manipulators in the literature such as adaptive control, computed torque and/or robust control [1, 6, 16]. For these systems, all joints are controlled as one MIMO system which makes their industrial implementation difficult. To overcome this problem, we propose in this work a hierarchical control strategy to solve the tracking control problem in the workspace for a 7-DOF hyper redundant articulated nimble adaptable trunks (ANAT) robot. The pseudo-inverse of the Jacobian is used to solve the inverse kinematics problem. The hierarchical control strategy consists in controlling the last joint while assuming that the

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remaining joints are stable and follow their desired trajectories. Then going backward, the same strategy is used for the (n-1)-th joint, i.e. controlling the (n-1)-th joint while assuming the remaining joints are stable and follow their desired trajectories, and so on until the first joint. Local stability is proved at each step. The hierarchical control strategy is implemented on the 7-DOF ANAT robot and gave a good workspace tracking.

The paper is organized as follows: section 2 presents the problem formulation and preliminaries. The hierarchical control strategy is presented in section 3. Section 4 presents the experimental results. Finally, conclusions are given in section 5.

II. PROBLEM FORMULATION AND PRELIMINARIES

The redundant robot considered in this paper is shown in figure 1. It has a 7-DOF: the first joint is prismatic, the second, third, fourth and fifth joints are redundant rotary joints followed by two rotary joints (joints 6, and 7) that represent the end effector. Generally, for n-DOF manipulator, the equation of motion can be written as [21]:

$$B(q)\ddot{q} + C(q,\dot{q}) + F\dot{q} + G(q) = \tau \qquad (1)$$

where $q \in \mathcal{R}^n$ denotes the vector of the generalized coordinates in the joint space, $\dot{q}$ and $\ddot{q}$ are the joints velocity and acceleration vectors respectively. $B(q) \in \mathcal{R}^{n\times n}$ is a symmetric positive definite mass and inertia matrix, $C(q,\dot{q})$ is the Coriolis and centrifugal forces vector, $F\dot{q} \in \mathcal{R}^n$ is the friction vector, $G(q) \in \mathcal{R}^n$ is a vector of gravity terms and finally $\tau \in \mathcal{R}^n$ is the joints input torque. The main propriety of the dynamical model that will be used for the control law is:

- the diagonal elements $B_{ii}(q)$ of the positive definite inertia and mass matrix $B(q)$ are positive [22]:

$$B_{ii}(q) > 0; \text{for i} = 1 \ldots \text{n} \qquad (2)$$

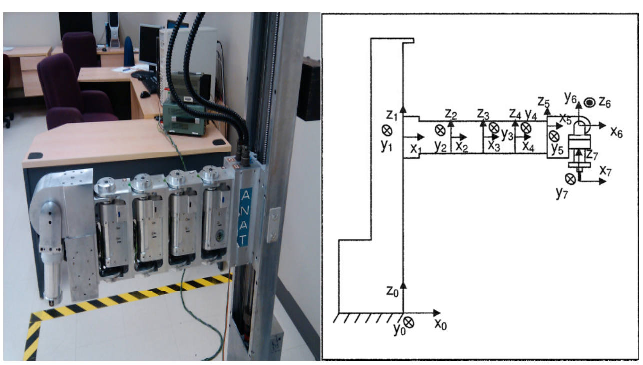

Fig. 1. ANAT robot axes system.

The objective of this work is to track a desired workspace trajectory. Three steps are considered to achieve this objective.

A. *Inverse kinematics*

In the first step, the inverse kinematics is performed. It consists in transforming the desired trajectory from the workspace to the joint space. The generalized inverse Jacobian matrix is applied to the redundant robot to express the relationship between velocities in the workspace and the joint space [15, 21]:

$$\dot{q} = J^T(J\,J^T)^{-1}\dot{X} \qquad (3)$$

where $J^T(J\,J^T)^{-1}$ is the generalized inverse Jacobian matrix and $\dot{q}$ and $\dot{X}$ are the velocities in the workspace and the joint space respectively.

B. *Control strategy*

In the second step, a hierarchical control strategy is considered. It consists in controlling each joint by following a hierarchical form. We start by the last joint, assuming that the (n-1) remaining joints are stable. We develop a control law for the n-th joint using a feedback linearization approach. Secondly, we apply the same strategy for the (n-1)-th joint by assuming that the remaining joints are stable. This strategy is then applied backward until the first joint.

C. *Direct kinematics*

The direct kinematics is used, in the third step, to transform the position of the ANAT robot from the joint space to the workspace The position of the tool relative to the base reference is given by [21]:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} L_4 c_{2345} s_6 + L_3 c_{2345} + L[c_{234} + c_{23} + c_2] + L_1 \\ L_4 s_{2345} s_6 + L_3 s_{2345} + L[s_{234} + s_{23} + s_2] \\ -L_4 c_6 + L_2 + q_1 \end{bmatrix} \qquad (4)$$

where $s_i = sin(q_i)$, $c_i = cos(q_i)$, $s_{ij} = sin(q_i + q_j)$, $c_{ij} = cos(q_i + q_j)$and L, L_1, L_3, L_4 are given in Table 1.

Table 1. Denavit-Hartenberg parameters of ANAT robot

Joints	$\boldsymbol{\alpha_{i-1}}$	$\boldsymbol{a_{i-1}}$	$\boldsymbol{d_i}$	$\boldsymbol{\theta_i}$
1	*0*	*0*	d_1	*0*
2	*0*	L_1	*0*	q_2
3	*0*	L	*0*	q_3
4	*0*	L	*0*	q_4
5	*0*	L	L_2	q_5
6	$\pi/2$	L_3	*0*	q_6
7	$-\pi/2$	*0*	$-L_4$	q_7

III. HIERARCHICAL CONTROL STRATEGY

In this section we apply the control strategy presented in section II-B. The dynamic model of the n-DOF manipulator given in (1) can be written as follow:

$$\begin{bmatrix} B_1^T(q) \\ \vdots \\ B_n^T(q) \end{bmatrix} \begin{bmatrix} \ddot{q}_1 \\ \vdots \\ \ddot{q}_n \end{bmatrix} + \begin{bmatrix} C_1(q,\dot{q}) \\ \vdots \\ C_n(q,\dot{q}) \end{bmatrix} + \begin{bmatrix} F_1\dot{q}_1 \\ \vdots \\ F_n\dot{q}_n \end{bmatrix} + \begin{bmatrix} G_1(q) \\ \vdots \\ G_n(q) \end{bmatrix} = \begin{bmatrix} \tau_1 \\ \vdots \\ \tau_n \end{bmatrix} \qquad (5)$$

where: $B_i^T(q) = [B_{i1}(q) \quad B_{i2}(q) \quad \dots \quad B_{in}(q)]$.
New generalized coordinate for the n-th joint is defined where the last joint is the controlled variable and the remaining joints (1, …, n-1) are assumed to be stable and follow their desired trajectories:

$$\overline{q}_n = [q_{1d} \quad \cdots \quad q_{(n-1)d} \quad q_n(t)]^T \tag{6}$$

$$\dot{\overline{q}}_n = [\dot{q}_{1d} \quad \cdots \quad \dot{q}_{(n-1)d} \quad \dot{q}_n(t)]^T \tag{7}$$

$$\ddot{\overline{q}}_n = [\ddot{q}_{1d} \quad \cdots \quad \ddot{q}_{(n-1)d} \quad \ddot{q}_n(t)]^T \tag{8}$$

Then, the equation of motion of the n-th joint becomes:

$$B_n^T(\overline{q}_n)\ddot{\overline{q}}_n + C_n(\overline{q}_n, \dot{\overline{q}}_n) + F_n\dot{q}_n + G_n(\overline{q}_n) = \tau_n \tag{9}$$

We propose the following control law for the last joint:

$$\tau_n = B_{nn}(\overline{q}_n)u_n + B_{n1}(\overline{q}_n)\ddot{q}_{1d} + \cdots + B_{n(n-1)}(\overline{q}_n)\ddot{q}_{(n-1)d} + C_n(\overline{q}_n, \dot{\overline{q}}_n) + F_n\dot{q}_n + G_n(\overline{q}_n) \tag{10}$$

where u_n is the new control law given by:

$$u_n = \ddot{q}_{nd} + K_{dn}\dot{\tilde{q}}_n + K_{pn}\tilde{q}_n \tag{11}$$

$\ddot{q}_{nd}$ is the desired acceleration for the n-th joint, $\tilde{q}_n = q_{nd} - q_n$ is the tracking error, and K_{dn} and K_{pn} are positive constants.
For stability analysis, inserting the control law (10) in the equation of motion (9), we get:

$$\ddot{q}_n = u_n \tag{12}$$

Using (11), the error dynamics becomes:

$$\ddot{\tilde{q}}_n + K_{dn}\dot{\tilde{q}}_n + K_{pn}\tilde{q}_n = 0 \tag{13}$$

Since K_{dn} and K_{pn} are positive constants, then the error dynamics is asymptotical stable.
Now, we go backward to the (n-1)-th joint and so on until the first joint by following the same strategy. Taking, for example, the i-th joint the equation of movement is given by the following expression:

$$B_{i1}(\overline{q}_i)\ddot{q}_{1d} + \cdots + B_{i(i-1)}(\overline{q}_i)\ddot{q}_{(i-1)d} + B_{ii}(\overline{q}_i)\ddot{q}_i + \cdots + B_{i(i+1)}(\overline{q}_i)\ddot{q}_{(i+1)d} + \cdots + B_{in}(\overline{q}_i)\ddot{q}_{nd} + C_i(\overline{q}_i, \dot{\overline{q}}_i) + F_i\dot{q}_i + G_i(\overline{q}) = \tau_i \tag{14}$$

where the new generalized coordinate is given as follows:

$$\overline{q}_i = [q_{1d} \quad \cdots \quad q_{(i-1)d} \quad q_i \quad q_{(i+1)d} \quad \cdots \quad q_{nd}]^T \tag{15}$$

$$\dot{\overline{q}}_i = [\dot{q}_{1d} \quad \cdots \quad \dot{q}_{(i-1)d} \quad \dot{q}_i \quad \dot{q}_{(i+1)d} \quad \cdots \quad \dot{q}_{nd}]^T \tag{16}$$

$$\ddot{\overline{q}}_i = [\ddot{q}_{1d} \quad \cdots \quad \ddot{q}_{(i-1)d} \quad \ddot{q}_i \quad \ddot{q}_{(i+1)d} \quad \cdots \quad \ddot{q}_{nd}]^T \tag{17}$$

Then we propose the following control law:

$$\tau_i = B_{i1}(\overline{q}_i)\ddot{q}_{1d} + \cdots + B_{i(i-1)}(\overline{q}_i)\ddot{q}_{(i-1)d} + B_{ii}(\overline{q}_i)u_i + \cdots + B_{i(i+1)}(\overline{q}_i)\ddot{q}_{(i+1)d} + \cdots + B_{in}(\overline{q}_i)\ddot{q}_{nd} + C_i(\overline{q}_i, \dot{\overline{q}}_i) + F_i\dot{q}_i + G_i(\overline{q}) \tag{18}$$

where u_i is the new control law given by:

$$u_i = \ddot{q}_{id} + K_{di}\dot{\tilde{q}}_i + K_{pi}\tilde{q}_i \tag{19}$$

$\ddot{q}_{id}$ is the desired acceleration for the i-th joint, $\tilde{q}_i = q_{id} - q_i$ is its tracking error, and K_{di} and K_{pi} are positive constants chosen such as the following dynamics error is stable.

$$\ddot{\tilde{q}}_i + K_{di}\dot{\tilde{q}}_i + K_{pi}\tilde{q}_i = 0 \tag{20}$$

The procedure of the control strategy is given in figure 2.

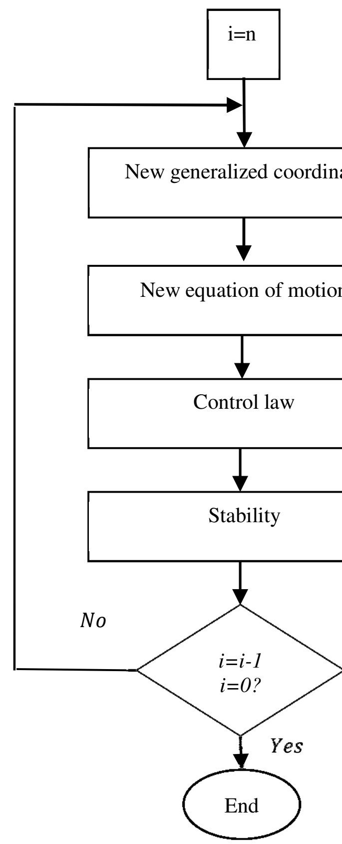

Fig. 2. Control strategy

IV. EXPERIMENTAL RESULTS

In this section, experimental results are presented by applying the previous strategy to the ANAT robot. In this paper, we consider the first prismatic joint and the following four joints, and we suppose that the sixth and seventh joints are locked.

The control strategy presented in the previous section was tested on the ANAT manipulator to track a desired trajectory in rectangular form. It was implemented using Simulink and Real-Time Workshop (RTW) of Mathworks®. For the real time target, we use the national Instruments PCI 6024E and the ATMEGA 16 microcontrollers are used to translate signals to serial peripheral interface (PSI).

Fig. 3. ANAT robot

The workspace trajectory is defined using Matlab/Simulink and the generalized inverse Jacobian matrix is used to transform the desired trajectory from the workspace to the joint space as described previously. Using the desired trajectory of the joints and their real values from the microcontrollers, the control algorithm executes and sends the computed torques to the microcontrollers. The microcontrollers translate the control signals into pulse width modulation (PWM) signals. The latter are applied to the H-bridge drive of the actuators of the ANAT robot. The current of each actuator is measured by a current sensor located in the H-bridge drive. The microcontrollers process the digital information of the actuators encoders and send the angles positions to Simulink. The real-time setup is given in Figure 4.

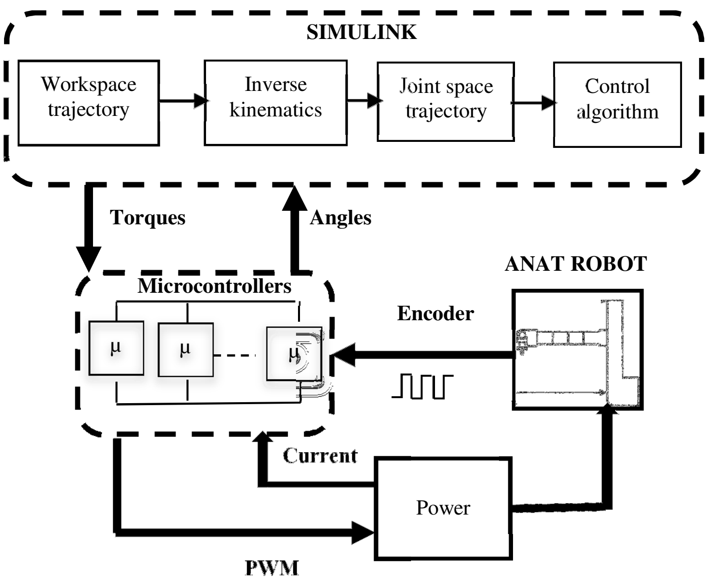

Fig. 4. Real-Time setup.

The controller gains are chosen by using a trial and error method as follows: $K_{p1} = 80, K_{p2} = 35, K_{p3} = 25,\ K_{p4} = 25,\ K_{p5} = 20;\quad K_{d1} = 80, K_{d2} = 1.85, K_{d3} = 2, K_{d4} = 12, K_{d5} = 12$; Figures 5, and 6 show trajectory tracking in the workspace, and in the joint space, respectively, while Figure 7 shows the error tracking in the joint space.

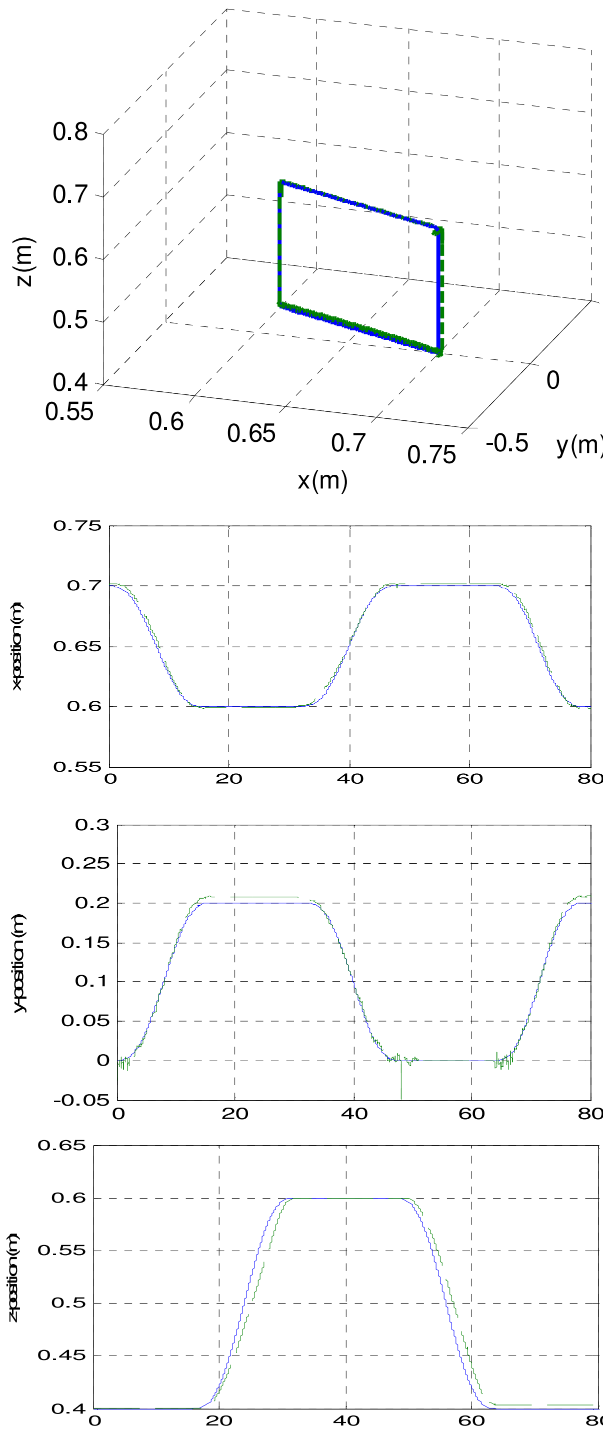

Fig. 5. Workspace tracking trajectories.

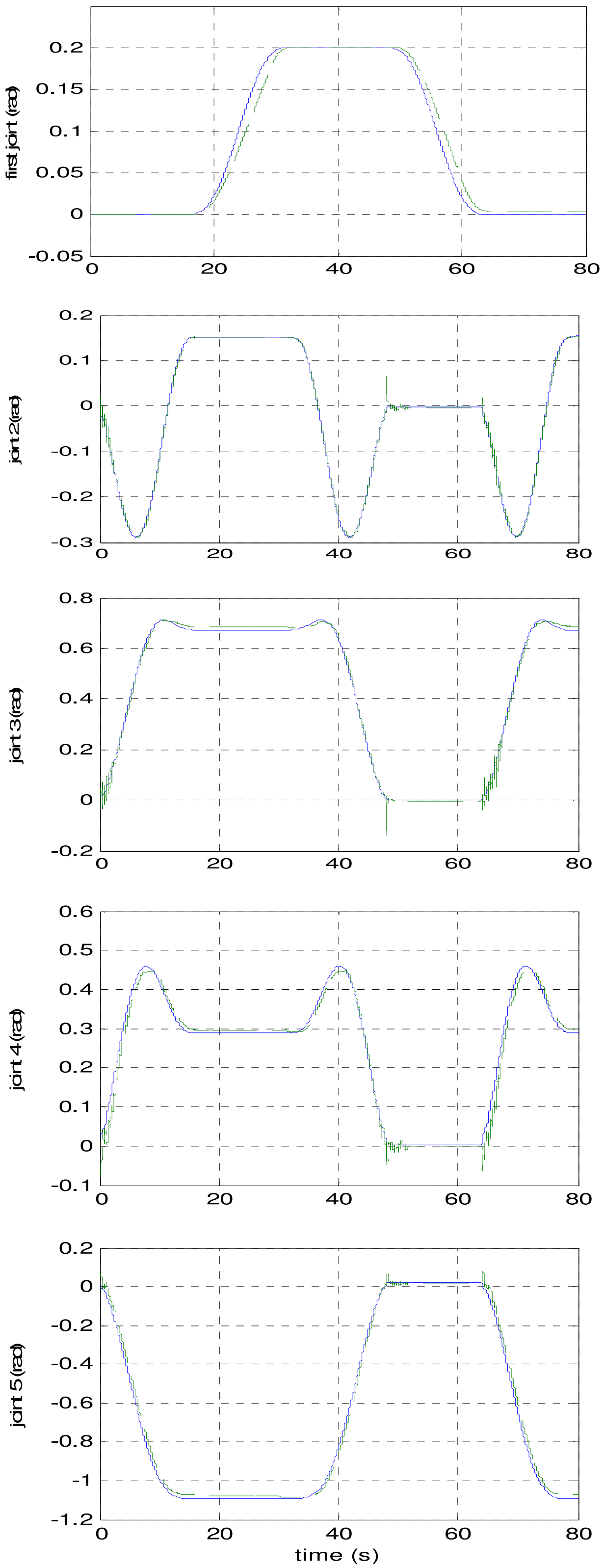

Fig. 6. Joint space tracking.

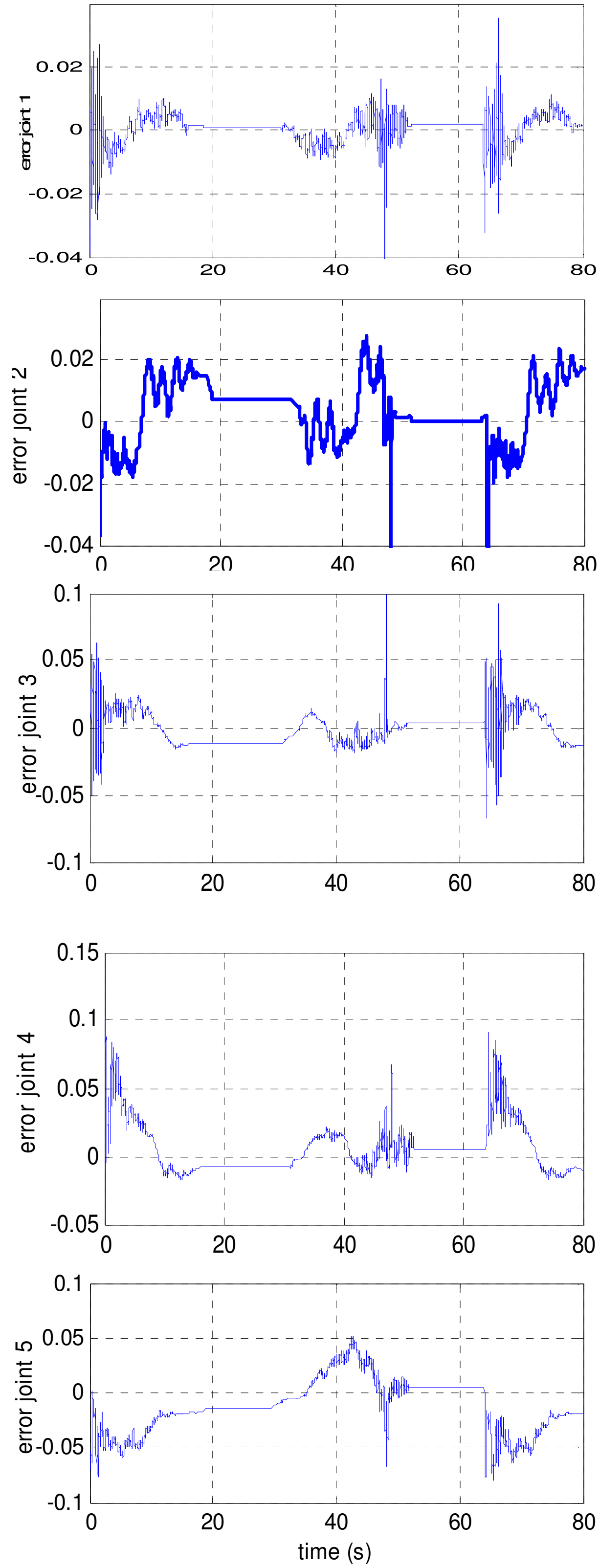

Fig. 7. Tracking errors in joint space.

According to the experimental results we can observe: a good tracking in the workspace (Figure 5). The workspace trajectory is obtained through the direct kinematics. Figure 6 shows a good tracking in joint space given by the inverse kinematics. This good tracking is confirmed in Figure 7 which shows the tracking errors in the joint space. . The tracking errors presented in Figure 7 show a small error less than 0.075rad. The very small errors of tracking confirm the effectiveness of the hierarchical control strategy.

V. CONCLUSION

This paper presents a new hierarchical control strategy. It consists in controlling each joint separately by starting with the last joint and going backward until the first joint. For each joint, we assume that the remaining joints are stable and follow their desired trajectories. Feedback linearization approach is used to develop the control law. Experimental results show a good tracking in the workspace that shows the effectiveness of the hierarchical control strategy. Local stability is proved for each joint but it is important to prove the globally stability in the future works.

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