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Backstepping Controller for Electrically Driven Flexible Joint Manipulator Under Uncertainties

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Article Info	ABSTRACT
	The grown complexity of the robot manipulators dynamics taking into account the joint flexibility, parameter uncertainties and unknown bounded disturbances makes conventional control strategies difficult and complex to synthesize. This paper focuses on the investigation into backstepping control of flexible joint manipulator driven by Brushless DC Motor (BDCM) in the presence of parameter uncertainties and unknown bounded disturbances for tracking trajectory. The goal of this paper is to compensate all uncertainties and disturbances for flexible join tmanipulator. To study the effectiveness of the controllers, backstepping controller has been developed for position control and an hysteresis controller has been treated for current control. Simulation results of the response of the flexible joint manipulators associated with their controllers have been presented. The high performances of the backstepping control are examined in terms of tracking accuracy and error reduction.

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1. INTRODUCTION

The problem of tracking trajectory for flexible joint manipulator has received a considerable breakthrough in last decades. In fact, multiple applications necessitate using flexible joint manipulator such as space manipulators (1), manipulators used in the medicine and home automation fields(2). Besides, model uncertainties and bounded unknown disturbances can cause significant deviations between desired and real trajectories due to unknown or changing flexible joints or unmodelled dynamics or modelling errors (3; 4). That's why; conventional or traditional controllers couldn't yield to good performance and dynamic behaviour(5). Recentattention has been including both flexible joints and actuator's dynamics to design control strategy to guarantee high performance in terms of tracking capability and attainable position. However, including actuator dynamics increases the system order, so the complexities to obtain robust control strategy. Infact, backstepping approach was used in multiple engineering fields such as electric machines and nonlinear systems especially robotic systems to benefit from its possibility to design robust nonlinear controllers that limit the effect of parameter uncertainties and unknown disturbances (6; 7; 8).

Several researches have addressed the control of flexible joint manipulator using backstepping method cited the work done by Nicosia and Tomei (9). Besides, three types of backstepping controller based on exact model knowledge, adaptive controller to compensate parameter uncertainties and unknwon disturbances have been presented by Bridges et al (10). Moreover, an adaptive controller based on backstepping design has been proposed by Yim et al (11) and Oh et al (12). In this paper, the tracking problem for electrically driven flexible joint manipulator is studied unde runcertainties and disturbances. The main contribution of this paper is to extract an adequate and precise controller for flexible joint manipulator including the dynamic model of the BDCM which increases the complexity. This paper is organized as

follows: in the second section, the flexible joint manipulator driven by Brushless DCMotor (BDCM) has been presented. In the thirds ection, both backstepping controller and hysteresis controller are studied respectively for controlling position and for controlling currents. In the fourth section, simulation results have been carried out in Simulink Matlab environment to show the performances of the different control techniques and their challenge to compensate uncertainties and disturbances.

2.   ELECTRICALLYDRIVENFLEXIBLEJOINTMANIPULATORMODEL

The dynamics of a single flexible joint manipulator can be described by the following equations (13; 14; 15; 16) :

$$\dot{x}_1 = x_2 \tag{1}$$

$$\dot{x}_2 = -\frac{m_1 g l_1}{J_1} sin(x_1) - \frac{K}{J_1}\left(x_1 - \frac{x_3}{\eta N}\right) + \frac{\Gamma_d}{J_1} \tag{2}$$

$$\dot{x}_3 = x_4 \tag{3}$$

$$\dot{x}_4 = \frac{K}{J_m}\left(x_1 - \frac{x_3}{\eta N}\right) + \frac{\Gamma}{J_m} \tag{4}$$

Where

x1=q is the link position, x2=˙ q is the link speed, x3=Θ is the motor position, x4=˙ Θ is the motor speed, m1 is the link mass, g is the gravity, l1 is the link length, J1 is the link inertia, Jm is the motor inertia, K is the joint stiffness,Γ is the torque applied to the axe,Γ $_d$ is the external torque, N is the reduction report, η is the efficiency of the gearbox.

The model of the flexible articulation is composed of an engine torque control driving a load through a transmission box similar to a torsion spring of linear characteristic. In fact, most of mechanic system are not perfectly rigid and we should take flexibility into consideration in the dynamic model of the robot to be more near to the reality and analyze a more precise controller. In our case, the flexibilities are located at the joints and as in most of the time, we add springs in series with the transmission such as shown in the figure 1.
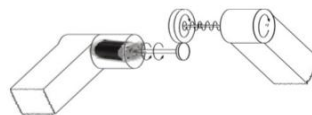

Figure 1. Flexible joint manipulator

2.1. ActuatorModel

The Brushless Direct Current Motor BDCM is a three phase synchronous motor. Using the inverter, we will supply the three motor coils such as shown in the Figure 2.
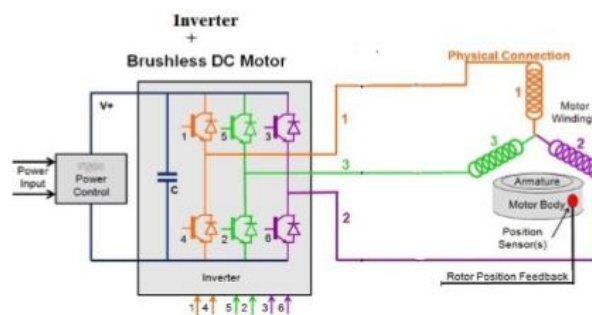

Figure 2. Inverter Brushless DC Motor (BDCM) association
The electrical equation of brushless DC motor per phase is written as follows (17):

$$\frac{dI}{dt} = -\frac{R}{L}I + \frac{V - E}{L}$$ (5)

Then,   the mechanical brushless DC motor equation is expressed by the following expression:

$$\frac{d\Omega_m}{dt} = -\frac{f}{J_m}\Omega_m + \frac{C_{em} - C_m}{J_m}$$ (6)

where:

a.   E is the electromotive force (emf),
b.   I is the current in the phases of motor,
c.   Cem andCm are the Electromagnetic and load torques of the motor respectively,
d.   f represents the friction,
e.   Jm is the inertia of the motor,
f.   Ωm is the velocity of the motor,
g.   V is the tension in the phases of the motor,
h.   L is the inductance of the motor,
i.   R is the resistance of the motor,
j.   KE and Kt are constants.
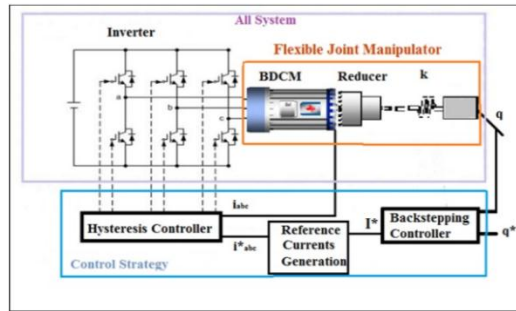k.

With : $E = KE\Omega m$ and $Cem = KtI$.

Figure 3. Flexible Joint Manipulator Control Strategy

3. CONTROLSTRATEGY

The control strategy implemented in the flexible joint manipulator driven by BDCM is given by Figure 3: The objective is to design a backstepping controller to remain the system behaviour to the desired trajectories, despite the presence of uncertainties and disturbances.

Table 1. Different Combination of the States of the Switches of a
Conventional Interver Associated with a BDCM

IGBT/ diode	Sequence 1		Sequence 2		Sequence 3		Sequence 4		Sequence 5		Sequence 6	
	seq_1^m	seq_1^g	seq_2^m	seq_2^g	seq_3^m	seq_3^g	seq_4^m	seq_4^g	seq_5^m	seq_5^g	seq_6^m	seq_6^g
S1	OFF	OFF	ON	OFF	ON	OFF	OFF	OFF	OFF	OFF	OFF	OFF
S2	OFF	OFF	OFF	OFF	OFF	OFF	ON	OFF	ON	OFF	OFF	OFF
S3	ON	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	ON	OFF
S4	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	ON	OFF	ON	OFF
S5	ON	OFF	ON	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
S6	OFF	OFF	OFF	OFF	ON	OFF	ON	OFF	OFF	OFF	OFF	OFF
D1	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	ON	OFF	ON
D2	OFF	ON	OFF	ON	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
D3	OFF	OFF	OFF	OFF	OFF	ON	OFF	ON	OFF	OFF	OFF	OFF
D4	OFF	OFF	OFF	ON	OFF	ON	OFF	OFF	OFF	OFF	OFF	OFF
D5	OFF	OFF	OFF	OFF	OFF	OFF	OFF	ON	OFF	ON	OFF	OFF
D6	OFF	ON	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	ON

3.1. Hysteresis Controller

The topology of the inverter is given by Figure 6. Each branch of the inverter includes two IGBTs and diodes connected on anti-parallel with them (18). Moreover, each sequence of the control signals of the the IGBTs S1−6 throughout a period is divided into active sub-sequence and regenerative sub-sequence (18).

A summary of the states of the switches (IGBTs and diodes) in the different sub-sequences (motor and generators) is given in the table 1.

The outputs of the hysteresis controller determine the control signals for the IGBTs. Indeed, the principle of the hysteresis control is to maintain the measured current within a band of centered given width around the reference current Iref.

3.2. Backstepping Controller

The backstepping approach is a recursive design methodology. It involves a systematic construction of both feedback control laws and associated Lyapunov functions. The controller design is completed in a number of steps, which is never higher than the system order (n) (16; 19). The system described by the equations 4 can be represented by the following generalized expression:

$$\dot{x}_i = f_i(x_1,...x_i) + g_i(x_1,...x_i)x_{i+1} \tag{7}$$

$$\dot{x}_n = f_n(x_1,...x_n) + g_n(x_1,...x_n)u \tag{8}$$

where, $f_i(0) = 0$, $g_i(0) \neq 0$, $1 \leq i \leq n-1$ and u is the control law.
For each step (i), we consider x_{i+1} as a virtual control input which is expressed as follows:

$$\dot{x}_{i+1} = \frac{1}{g_i(x_1,...x_i)}(u_i - f_i(x_1,...x_i)) \tag{9}$$

$$\dot{x}_i = u_i \tag{10}$$

The Lyapunov function is chosen to guarantee the asymptotically stability of the system for $(x_1,...,x_i) = (0,...,0)$.

$$V_i = V_{i-1} + \frac{1}{2}(x_i - \varphi_{i-1})^2 \tag{11}$$

We choose also u_i as follows:

$$u_i = -\frac{\partial V_{i-1}(x_1,...x_{i-1})}{\partial x_{i-1}} - k_i(x_i - \varphi_{i-1}) + \sum \left(\frac{\partial \varphi_{i-1}}{\partial x_l}\dot{x}_l\right); \tag{12}$$

where, $1 \leq l \leq (i-1)$; $k_i > 0$.

So, the virtual control input is expressed as follows:

$$\dot{x}_{i+1} = \varphi_i = \frac{1}{g_i}\left(-\frac{\partial V_{i-1}(x_1,...x_{i-1})}{\partial x_{i-1}} - k_i(x_i - \varphi_{i-1}) + \sum \left(\frac{\partial \varphi_{i-1}}{\partial x_l}\dot{x}_l\right) - f_i\right) \tag{13}$$

At the final stage, we can determine the actual control law $u_n = \varphi_n$ as follows:

$$u_n = \frac{1}{g_n}\left(-\frac{\partial V_{n-1}(x_1,...x_{i-1})}{\partial x_{i-1}} - k_n(x_n - \varphi_{n-1}) + \sum \left(\frac{\partial \varphi_{n-1}}{\partial x_l}\dot{x}_l\right) - f_n\right) \tag{14}$$

Where, $1 \leq l \leq n-1$ and $k_n > 0$.

The backstepping controller is determined by calculating the torque u = Γ. So, the states x1,x2,x3,x4 are controlled to origin point (0,0,0,0), with the following four steps (16).

3.2.1. Step1
The first subsystem of 4 is:

$$\dot{x_1} = f_1(x_1) + g_1(x_1)x_2 \tag{15}$$

Where,

$$f_1(x_1) = 0,$$

$$g_1(x_1) = 1.$$

The candidate Lyapunov function is chosen as follows:

$$V_1 = \frac{1}{2}x_1^2 \tag{16}$$

Then, the virtual control input x2 = u1 is expressed as follows:

$$x_2 = u_1 = \varphi_1(x_1) = -k_1x_1 \tag{17}$$

3.2.2. Step2
Considering (x1,x2) of 4 is:

$$\dot{x_1} = f_1(x_1) + g_1(x_1)x_2 \tag{18}$$

$$\dot{x_2} = f_2(x_1,x_2) + g_2(x_1,x_2)x_3 \tag{19}$$

Where,

$$f_2(x_1,x_2) = -\frac{m_1gl_1}{J_1}sin(x_1) - \frac{K}{J_1}(x_1 + \frac{\Gamma_d}{J_1},$$

$$g_2(x_1,x_2) = \frac{K}{\eta NJ_1}.$$

The candidate Lyapunov function is chosen as follows:

$$V_2 = V_1 + \frac{1}{2}(x_2 - \varphi_1)^2 \tag{20}$$

Then, the virtual control input x3 = u2 is expressed as follows:

$$x_3 = \varphi_2(x_1,x_2) = \frac{\eta NJ_1}{K}(\frac{\partial \varphi_1}{\partial x_1}\dot{x_1} - \frac{\partial V_1}{\partial x_1} - k_2(x_2 - \varphi_1) - f_2(x_1,x_2) \tag{21}$$

3.2.3. Step3
Considering (x1,x2,x3) of 4 is:

$$\dot{x_1} = f_1(x_1) + g_1(x_1)x_2 \tag{22}$$

$$\dot{x_2} = f_2(x_1,x_2) + g_2(x_1,x_2)x_3 \tag{23}$$

$$\dot{x_3} = f_3(x_1,x_2,x_3) + g_3(x_1,x_2,x_3)x_4 \tag{24}$$

$$f_3(x_1, x_2, x_3) = 0,$$

$$g_3(x_1, x_2, x_3) = 1. \quad \text{Where,}$$

The candidate Lyapunov function is chosen as follows:

$$V_3 = V_2 + \frac{1}{2}(x_3 - \varphi_2)^2$$

(25)

Then,   the virtual control input x4 = u3 is expressed as follows:

$$x_4 = \varphi_3(x_1, x_2, x_3) = \frac{1}{g_3}(u_3 - f_3)$$

(26)

$$x_4 = \frac{\partial \varphi_1}{\partial x_1}\dot{x}_1 + \frac{\partial \varphi_2}{\partial x_2}\dot{x}_2 - \frac{\partial V_2}{\partial x_2} - k_3(x_3 - \varphi_2) - f_3(x_1, x_2, x_3)$$

(27)

3.2.4. Step 4

Considering (x1, x2, x3, x4) of 4 is: (29)

$$\dot{x}_1 = f_1(x_1) + g_1(x_1)x_2$$

(29)

$$\dot{x}_2 = f_2(x_1, x_2) + g_2(x_1, x_2)x_3$$

(30)

$$\dot{x}_3 = f_3(x_1, x_2, x_3) + g_3(x_1, x_2, x_3)x_4$$

(31)

$$\dot{x}_4 = f_4(x_1, x_2, x_3, x_4) + g_4(x_1, x_2, x_3, x_4)u$$

Where,

1. $f_4(x_1, x_2, x_3, x_4) = \frac{K}{J_m}(x_1 - \frac{x_3}{\eta N})$,

2. $g_4(x_1, x_2, x_3, x_4) = \frac{1}{J_m}$.

The candidate Lyapunov function is chosen as follows:

$$V_4 = V_3 + \frac{1}{2}(x_3 - \varphi_2)^2$$

(32)

Then,   the control law u =Γis expressed as follows:

$$u = \Gamma = \frac{\partial \varphi_1}{\partial x_1}\dot{x}_1 + \frac{\partial \varphi_2}{\partial x_2}\dot{x}_2 + \frac{\partial \varphi_3}{\partial x_3}\dot{x}_3 - \frac{\partial V_3}{\partial x_3} - k_4(x_4 - \varphi_3) - f_4(x_1, x_2, x_3, x_4)$$

(32)

4.   SIMULATION RESULTS
4.1. Description of Simulation

Table 2. System   Parameters

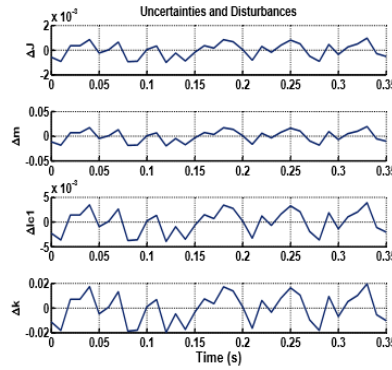| Symbol	Description	Numeric Value
R	Resistance	0.625Ω
L	Inductance	1.595e-3 H
J_m	Motor Inertia	$1e\text{-}5 Kg.m^2$
m_1	Manipulator Mass	0.8619 Kg
l_1	Manipulator Length	0.3 m
J_1	Manipulator Inertia	$0.0065 N.m^2$
N	Reduction Report	74
η	Gearbox Efficiency	0.72
f	Friction	$1.164e\text{-}3 Kg.m^2.s^{-1}$
K_t	Torque constant	0.0382
K_E	EMF constant	0.0382

Figure 4. Evolution of Curves of the Parameter Uncertainties and Torque Disturbances

To illustrate the performance of backstepping control for flexible joint manipulator, we have simulated this algorithm in the simulink matlab environment. The system parameters used for simulation are given in table 2.
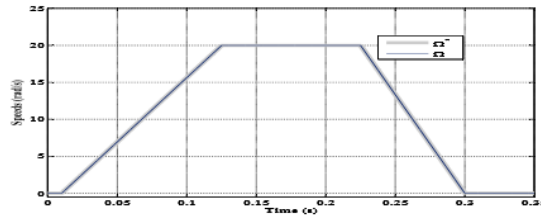

Figure 5. Evolution of the Speed

We have considered the uncertainties described in the following figure:
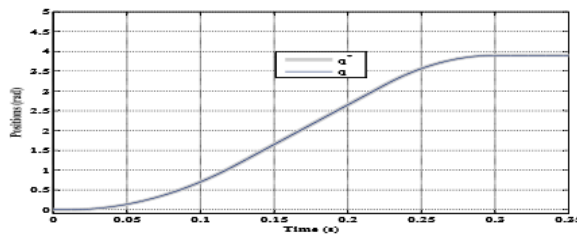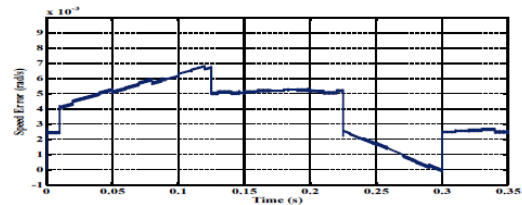

Figure 6. Evolution of the Position
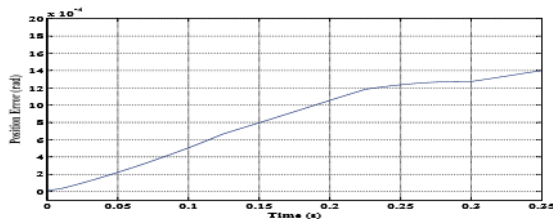

Figure 7. Evolution of the speed error
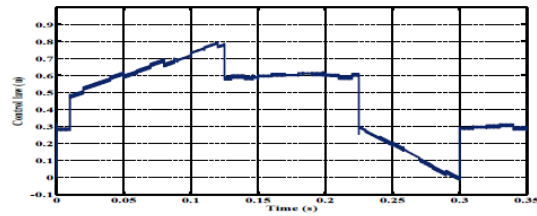

Figure 8. Evolution of the Position Error

Figure 9. Evolution of the Control Law

4.2. Simulation Analysis

As can see from figures 5, 6, 7, 8 and 9, the behaviors of reference and actual tracking trajectory performance for different parameter uncertainties and bounded disturbances are very similar. Then, we can show that the variation of parameter uncertainties and bounded disturbances causes the apparition of ripples in the different curves behavior. The adopted control strategy allows us to compensate of all uncertainties and disturbances which prove the high performances of the backstepping control for tracking problem.

5.   CONCLUSION

Many control techniques have been designed to flexible joint manipulator control in the presence of uncertainties and disturbances. However, the performances of control strategy are degraded due to the negligence of actuator part. This paper presents backstepping and hysteresis controllers of flexible joint manipulator driven by Brushless DC Motor (BDCM) under uncertainties and disturbances for tracking problem. To study the effectiveness of the controllers, backstepping controller has been developed for position control and an hysteresis controller has been treated for current control. To evaluate the performances, we have implemented the control strategies in matlab simulink environment. The simulation results prove that the control strategies are robust against all uncertain ties and disturbances.

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