A&QT-R 2004 (THETA 14)

2004 IEEE-TTTC - International Conference on Automation, Quality and Testing, Robotics

May 13 – 15, 2004, Cluj-Napoca, Romania

INDEPENDENT ROBOT JOINT CONTROLLER WITH LOAD TORQUE OBSERVER

Calin RUSU, Iulian BIROU

Department of Electric Drives and Robots
Technical University of Cluj, Baritiu Street, no.26
3400 Cluj, Romania; fax: +40-264-595520;
e-mail: calin.rusu@utcluj.ro

Abstract This paper presents the design of an independent robot joint controller with load torque observer. The motion control of a two-link robot, operating in horizontal plane, actuated with step motors is considered as final application. The dynamic performances of the stepper motor drive are improved by the field-oriented control. A current source PWM inverter fed the stepper motor which means that the system becomes like an ideal torque generator, very suitable for mechatronics applications. The field-oriented control of the motor drive allow an independent control of the torque and flux in the machine, which means that it works like a dc machine. In order to get the robustness against the parameters variation and external disturbances, an augmented state feedback control with load torque observer strategy is proposed. This control scheme is finally applied to the robot arm in order to prove its effectiveness for the path following trajectory applications. Simulation results are presented to illustrate the potential of the proposed controller.

Keywords: stepper motor, field-oriented, load torque observer, DSP controller

1. INTRODUCTION

For high performance motion control of multi-axis robot manipulators it is necessary to compensate various kinds of non-linear dynamical forces. The *computed torque method* requires an exact robot model and a large amount of real time computation of inverse dynamic. Current approach for industrial robots in control design is based on single joint dynamics because of the gear ratios and moderate speed of joints. The inference forces can be almost completely suppressed at each joint as an unknown disturbance. As a result, the *robust controllers* are adopted in case of robot arm joints.

Position control request an augmented state feedback controller based on linear quadratic law (LQC). Applying a field-oriented control to the stepper motor it becomes a high-dynamic AC-*servo*. The paper explores the feasibility for implementing the control scheme using a TMS320C31 digital signal processor.

2. STEPPER MOTOR DRIVE

The steppers are widely used in applications of positioning systems since they can be controlled with simple schemes as open-loop or closed-loop configuration. Both of these schemes control only the position and speed parameters. In applications with load torque variation, these classical schemes present poor dynamic performances. For the robots powered by stepper motor drives the used controllers are designed do not account by the robot dynamics. Under these circumstances we proposed to apply the field-oriented control to the stepper motor in order to improve considerable the dynamic performances for the stepper motor.

The full model of the motor consists of the two electrical dynamic equations of the stator windings and one equation for the mechanical dynamic of the rotor shaft [1]. Applying the **dq** *transformation,* the motor's model is converted into a *quadrature* oriented frame, fixed to the rotor given by the following state equations:

$$\begin{cases} \dfrac{di_{sd\theta}}{dt} = \dfrac{1}{L_{sd}}(u_{sd\theta} - R\cdot i_{sd\theta} + z_r\cdot\Psi_M\cdot\omega_m\cdot L_{sq}\cdot i_{sq\theta}); \\ \dfrac{di_{sq\theta}}{dt} = \dfrac{1}{L_{sq}}(u_{sq\theta} - R\cdot i_{sq\theta} - \omega\cdot L_{sd}\cdot i_{sd\theta} + z_r\cdot\Psi_M\cdot\omega_m); \\ \dfrac{d\omega_m}{dt} = \dfrac{1}{J_m}\cdot(k_m\cdot(\Psi_M\cdot i_{sq\theta} + (L_{sd} - L_{sq})\cdot i_{sd\theta}\cdot i_{sq\theta}) - B_m\cdot\omega_m - m_r); \\ \dfrac{d\theta_m}{dt} = \omega_m. \end{cases} \tag{1}$$

where:

L_{sd}, L_{sq} : inductivities; $i_{sd\theta}$: dθ - axis current; Ψ_M : permanent magnet; $i_{sq\theta}$: qθ - axis current;
θ_m : rotor position; $u_{sd\theta}$: dθ - axis voltage; ω_m : rotor speed; $u_{sq\theta}$: qθ - axis voltage;
z_r : number of teeth; R : resistance; J_m : inertia: B_m : viscous friction;
m_r : load torque, [2].

By field-oriented control, the current $i_{sd\theta}$ must be kept to zero [3], so as the condition of field-oriented to be fulfilled. That means the *decoupled* current component does not contribute to torque production. Under this circumstance, only the *quadrature* current component generates the torque, m_e. This makes possible to control independently the torque and flux in the stepper motor. The state equations (1) can be rewrite under the field-oriented condition as follow:

$$i_{sd\theta} = 0;$$

$$\frac{d}{dt}\begin{bmatrix}\omega_m \\ \theta_m\end{bmatrix} = \begin{bmatrix} -\dfrac{B_m}{J_m} & 0 \\ 1 & 0 \end{bmatrix}\cdot\begin{bmatrix}\omega_m \\ \theta_m\end{bmatrix} + \begin{bmatrix}\dfrac{k_m}{J_m} \\ 0\end{bmatrix}\cdot i_{sq\theta} + \begin{bmatrix} -\dfrac{m_r}{J_m} \\ 0 \end{bmatrix} \tag{2}$$

where the motor is fed by a current source PWM voltage inverter and $k_m = z_r\,\Psi_M$ is the torque constant.

3. POSITION CONTROLLER

The controller for the stepper motor drive described by (2) request to control two parameters: the current of *d-axis* ($i_{sd\theta}$) and the positions of the rotor shaft θ_m.

3.1. The d-Axis Current Control

As it is already know, the field orientation control imposes a zero value as reference for the *d*-axis current controller. The stepper motor being current controlled, made necessary to use a fast current controller to satisfying the principle of field orientation. A PI current control algorithm for *d*-axis, in order to achieved the field oriented control ($i_{sd\theta}=0$), is used.

3.2. Position Control

The *q*-axis current controller is employed to control the position of the rotor. For this controller we impose an augmented state variable feedback controller based on the linear quadratic law (LQC), given by the equation (3).

$$\frac{d}{dt}\begin{bmatrix}\omega\\ y\\ z\end{bmatrix}=\begin{bmatrix}-\dfrac{B_m}{J_m} & 0 & 0\\ 1 & 0 & 0\\ 0 & 1 & 0\end{bmatrix}\cdot\begin{bmatrix}\omega\\ y\\ z\end{bmatrix}+\begin{bmatrix}\dfrac{z_r\cdot\Psi_M}{J_m}\\ 0\\ 0\end{bmatrix}\cdot i_{sq\theta}-\begin{bmatrix}\dfrac{1}{J_m}\\ 0\\ 0\end{bmatrix}\cdot m_r-\begin{bmatrix}0\\ 0\\ 1\end{bmatrix}\cdot y_r \tag{3}$$

$$y=\begin{bmatrix}0 & 1 & 0\end{bmatrix}\cdot\hat{\bar{x}}$$

The rank of controllability matrix for this system is 3, which means that the steady state value of z variable becomes zero if the input control is given in the form of $u(t)=-\hat{k}\cdot\hat{x}$. The state feedback controller gain is determined by the optimal control law minimizing the performance index. A large feedback gain is needed for a fast reduction of error caused by the disturbance, which results in a very large current command. If the load torque is known an equivalent current command can be expressed in form of $m_r=k_t\cdot i_{qc}$. The equivalent *q–axis* current can be calculated to compensate the variation of load torque by using a feed forward term. The load torque observer is designed considering m_r as an unknown input. The observer also requests as inputs the motor currents and the position value. The system equation is expressed as follow:

$$\begin{bmatrix}\hat{\omega}\\ \hat{y}\\ \hat{m}_r\end{bmatrix}=\begin{bmatrix}a_1 & 0 & a_2\\ a_3 & 1 & a_4\\ 0 & 0 & 1\end{bmatrix}\cdot\begin{bmatrix}\hat{\omega}\\ \hat{y}\\ \hat{m}_r\end{bmatrix}+\begin{bmatrix}b_1\\ b_2\\ 0\end{bmatrix}\cdot i_{sq\theta}+\begin{bmatrix}l_1\\ l_2\\ l_3\end{bmatrix}\cdot\left(y(k)-\begin{bmatrix}0 & 1 & 0\end{bmatrix}\cdot\begin{bmatrix}\hat{\omega}\\ \hat{y}\\ \hat{m}_r\end{bmatrix}\right) \tag{4}$$

with l_1,, l_2 and l_3 are the elements of L matrix.

4. SIMULATION AND EXPERIMENTAL RESULTS

The Simulink® model for the proposed system drive is used. Fig. 1 shows the top level simulation run on the position control scheme, using as position reference an input unit. The initial task was to create the models for the stepper motor controlled by field-oriented, state feedback controller and load torque observer. Some of these models are made as *S*-functions, considering the previous relations (2), (3) and (4), respectively. For the torque observer the position (θ_m) and the phase currents (i_{sa}, i_{sb}) are the inputs and estimated velocity ($\hat{\omega}_m$) is the output. The load torque disturbance is compensated by feed forwarding the equivalent current i_{sqL} to the controller output current $i^*_{sq\theta}$. Including these models, the controller and plant as SIMULINK® block within a simulation run, a hierarchical design is adopted.

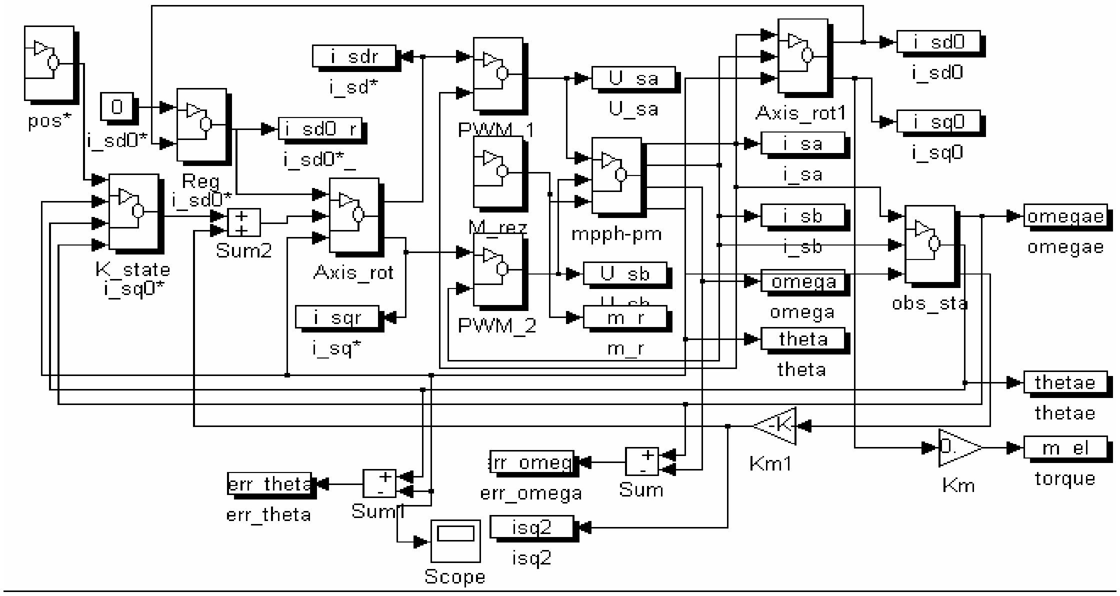

Figure 1. SIMULINK model

The experimental results are obtained by plotting the data logger stored in the DSP data memory at each sampling time. The C code for the TMS320C31 SPB Model 31 controller is generated from Simulink® scheme using *The Real-Time Workshop* code generation environment. The real-time code is compiled on the host using the DSP cross compiler and the object file (in COFF format) is downloaded into the program memory of the TMS320C31 target system. The real time simulation for the proposed system is presented in Fig 2. The experimental results show that the proposed control work well even in the case of a load torque variation.

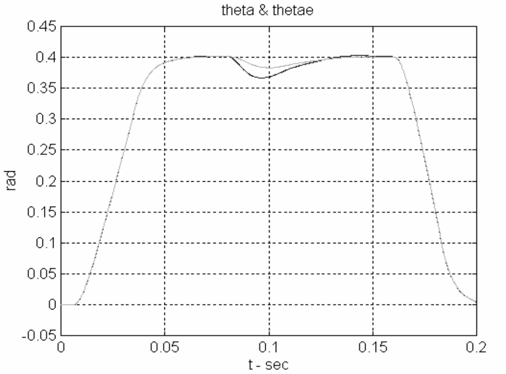

Figure 2a. θ_m - Position;

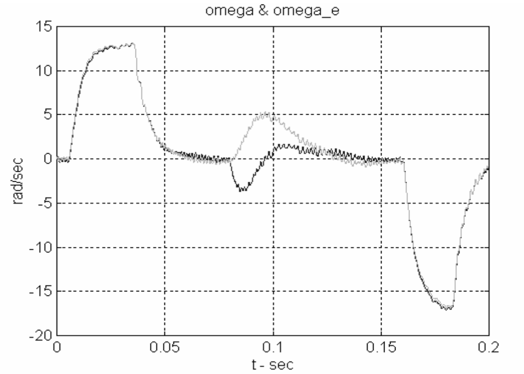

Figure 2b ω_m - speed & estimated speed

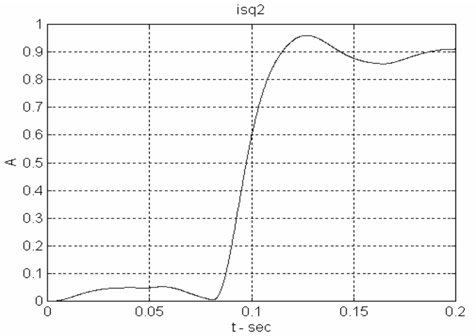

Figure 2c. i_{sqL}. - The equivalent load current

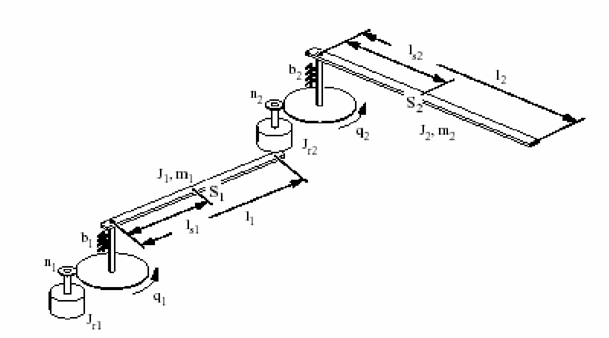

Figure 3. 2-DOF robot arm

The system drive was designed to control a robot axis joint. In order to investigate the dynamic behavior of proposed controller, a 2-links robotic arm, presented in Fig. 3 was taken into account. Both joints are driven by stepper motors mounted, via a gearing mechanisms with ratios n_1=n_2=10. The dynamic behavior for such a robot is very well known.

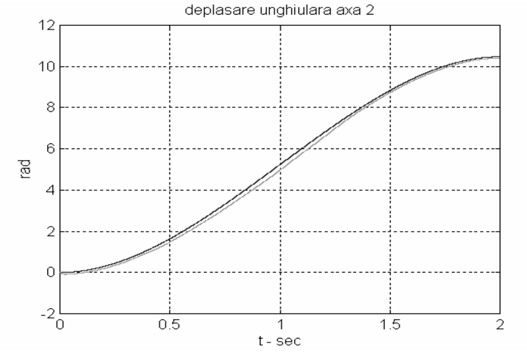

Figure 4a. θ_s - position (desire & real)

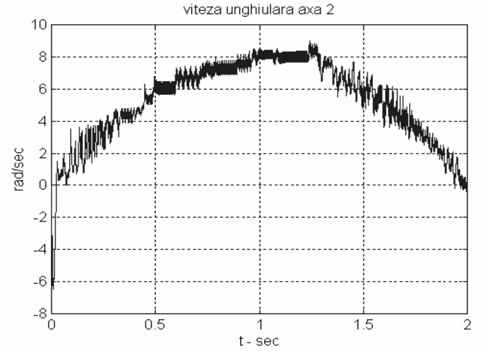

Figure 4b. speed of the first joint

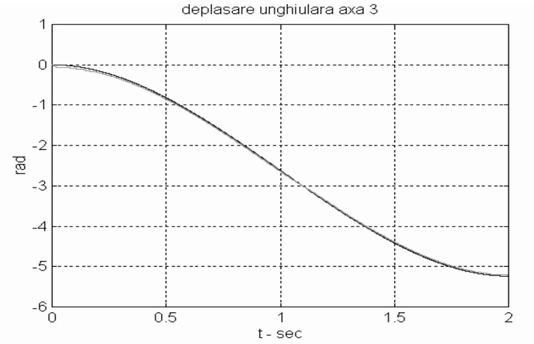

Figure 4a. θ_e - position (desire & real)

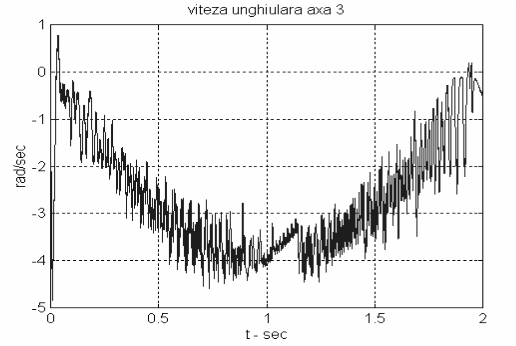

Figure 4b. ω_3 – speed of the second joint

For experimental, the desired joint trajectories was considered as two third-order polynomials interpolated between θ_s = [0° 60°] and θ_e=[0° -30°] respectively, with zero desire velocities and accelerations at t=0 and t=2 second. The torque variations along the imposed trajectory at the joints level were simulated and introduced as input disturbances. The real-time simulation results for the robot arm powered by the proposed system drive with load torque observer (one for each joint) are presented in the Fig. 4.

CONCLUSIONS

This paper describes an independent robot joint controller system. This strategy combines a linear quadratic controller with a load torque observer. The simulation results shows a better tracking accuracy of joint trajectories, without using the dynamic model of the robotic arm. A systematic approach was developed for stepper motor drives with field-oriented control. The LQC plus load torque observer is designed in state space analysis. Considering the load torque as the unknown input, the control system is implemented based on the observer theory.

REFERENCES

[1] Imecs M., Kelemen A., Rusu C., Marschalko R.. -"Vector control of PM hybrid stepping motor with tracking torque". 7th International Conference IMACS-TC1'93, 7-8-9 July 1993, Montreal, Canada.
[2] Kelemen A., Imecs M., Marschalko R., Rusu C. -"Torque and Speed Control Systems for PM Hybrid Stepping Motor". ICEMA, Adelaida, Australia, vol. 3, pp. 506-512, 13-15 Sept 1993.
[3] Imecs M., Rusu C.. -"Variable structure control of microrobot servo drive with field-oriented PM step motor"- EPE Chapter, Lausanne 1994, pp. 301-306.
[4] Bodson M. et al. - High Performance Nonlinear Feedback Control of a Permanent Magnet Stepper Motor. IEEE Trans on Control System Technology, vol.1, no.1, pp.5-13.
[5] Kellermann H. et al. - Field Oriented Position Control of a Hybrid Stepper Motor, European Power Electronics EPE 95, Sevilla, Spain., vol.3, pp.908-913.