A Two Freedom Degree Manipulator Control for a Wooden Rotulator based on PIC Microcontrollers

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Abstract—This document presents the X, Y y Z movement control of a manipulator with two freedom degree. It is shown its application as a wood letterer in two dimensions. The manipulator uses permanent magnet CD motors. The design of the manipulator velocity and position motor control is based on Microchip microcontrollers using full bridge converters using the pulse wide modulation technique. The manipulator control system includes a computer used as a user interface, where the user can draw the figure to be lettered. From this information the computer generates velocity and position commands for each mechanism. The document describes in detail the software and hardware used for the controller.

Index Terms—Controller, Manipulator, PWM, Microcontroller

I. INTRODUCTION

NOWADAYS, robot manipulators are used in many industrial applications. They are used to lettering pieces, to cut materials with special forms, as graphic machines, as crane, as drills. An the heart of every manipulator there is a control system which will control each and every one of the servomechanisms so they can have the right position and velocity of each of their corresponding motor shaft [1], [2], [3]. This document presents the design of the three axis manipulator controller. Experimentally, this manipulator has been applied to an ultrasonic essay, to position the ultrasonic emisor/sensor. These works were realized with another type of micro controllers (Intel 80C196KC) and more complex hardware [4]. The design presented in this document is more compact and smaller 8 bit micro controllers are used. The manipulator is a cartesian type (plane X-Y) mounted on an aluminum structure. The final effecter or tool is mounted on the Z axis [4]. The servomechanism is based on permanent magnet CD motors, which were chosen because of its high start torque, efficiency and its control easiness [5]. The control system has a distributed architecture. It has an independent control system for each servomechanism and a master controller for its synchronization. Each servomechanism control for the X, Y, Z axis is based on a 8 bit Microchip family microcontroller [6]. Each motor is feed by an full bridge cd-cd electronic converter using the pulse wide modulation (PWM) technique. To calculate the speed and position, a 256 pulses per turn digital encoder is used coupled to the shaft of each of the motors. This document describes in detail the software and hardware used for the controller.

II. SERVOMECHANISM STRUCTURE

Figure 1 shows a picture of the structure of the manipulator. The manipulator general structure has a cartesian geometry with two freedom degrees for the cartesian XYZ movement. The microcontroller previously described were chosen because they presented several advantages compared to the others such as: the nominal velocity, low cost, some of them have quadrature coders for encoders for position and velocity measurements, PWM outputs, USB communication, easiness to program, among other characteristics.
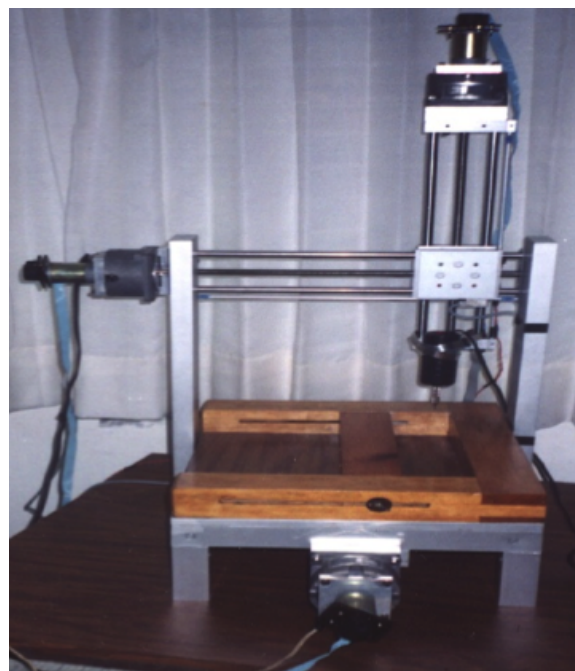

Fig. 1. The manipulator

The block diagram in figure 2 shows the implemented controller general structure to handle the manipulator.
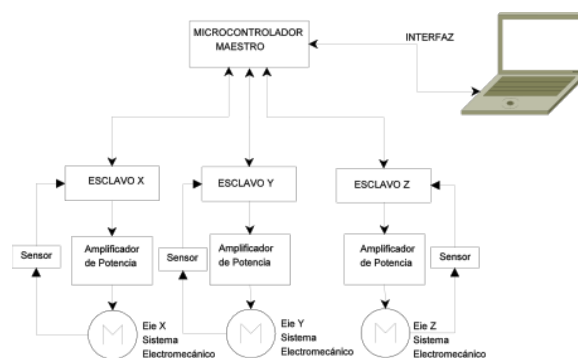

Fig. 2. Manipulator Structure

Figure 2 presents : A master microcontroller who will perform the communications tasks with the computer as well as coordinate the XYZ displacements. The computer which will send information about the traces to follow to realize the lettering of the drawn picture. Three slave microcontrollers will be in charge of the closed loop control of the displacements and traces of each of the motors which move the the axis, and send a signal to the master when a trace is finished or if they are at he origen of each axis. Now we will briefly describe the function of the elements of the blocks diagram.

- *Interface.* It is in charge of the graphical communication with the end user. It sends the coordinates to make the routing of the figures. It is also the one in charge to make the transformations of the position commands which are entered in form of coordinates XYZ into pulses referring to the positions of each motor and the speed which each one of them has to move. This was developed in Matlab.
- *Master Microcontroller.* This is a PIC18F4550 micro controller [8]. This is in charge of receiving the position and velocity commands from the computar for each axis, to send them to the slave microcontrollers. This is also in charge the signals from the slaves the signals which indicates that they are already in the reference position in each axis, synchronizes the movement of the axis.
- *Slave Microcontrollers.* They are PIC18F2431 micro controllers [8]. They are in charge of the closed loops control for the motors of the axis XYZ independently, the displacement on each axis, and to finish such displacements.
- *Power Amplifier.* This is a CD-CD full bridge converter built cased on MOSFETs. This amplifier receives the PWM signal from the slave, and converts it to the adequate voltage and current levels to activate the corresponding motor [5].
- *Electromecanic System.* It comprises by a CD motor, a 75 to 1 relation step-down gear box, a worm gear to convert the rotational movement into lineal movement with a 0.3cm per turn and the load to be displaced.
- *Sensors.* There are two kind or sensors: the encoder monuted on the shaft of each motor, and the magnetic, mounted on each axis. The encoder is a HP series HEDS-5000with a 256 slots disk [10]. It provides the microcontroler a digital signal corresponding to the motor shaft position and direction, as well as the cero position of the manipulator. The magnetic sensor provides the initial reference position and is located at the origen of the respective moving axis

III. POSITION CONTROL ALGORITHM

The control is a the key factor as it determines how useful the manipulator will be in the applications. The objective of the control algorithm is to generate the control action signals in such a way that the manipulator follow the position. The computer determines the displacements and the speed relation of each servomechanism and send them to the master who will transfer them to each of the axis. The position and velocity of the rotor shaft are related by equation 1.
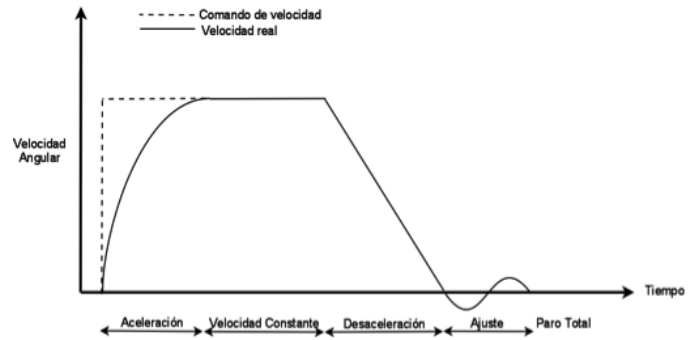

Fig. 3.   Wanted speed profile

$$\theta = \int \omega \mathrm{d}t \qquad (1)$$

This implies that if we want to control the position then we must control the velocity. In this development the velocity profile shown in Figure 3 for each axis was chosen [11].

We can distinguish the following regions in this profile:

- *Acceleration.* The error position counter sends a command to obtain the maximum speed. The rotor speed up according to the motor dynamical equation and speed velocity controller used.
- *Constant speed.* When the rotor reaches the maximum speed set, the speed controller mantains constant such speed.
- *Deceleration.* To decelerate the motor with constant torque, the speed command must be according to equation 2

$$\omega_c = \sqrt{2q\beta} \qquad (2)$$

where
- q Actual position error (the difference of the wanted value and the actual position value given in pulses of the encoder mounted on the motor shaft.
- β Negative acceleration o deceleration rate in $pulses/sec^2$. It depends on the motor parameters.

- *Adjust.* Ideally the motor must stop in the wanted position and must not move beyond when the controls is driver exactly by 2. I practice, however, there are always the possibility for the rotor to go beyond the wanted position, because of the data of the speed command are not given as an idle linear function, but in discontinuos form as a result of the digital quantization. Normally, the control system is designed in such a way that the rotor eventually will stop in the wanted position after several oscilation cycles around the reference.
- *Stop.* When the rotor stops at the wanted position, the controller sends the needed torque to maintain it is that position.

To achieve the wanted profile, shown in Figure 3, the controller generates the reference speed commands which deepen on the position error according to the following rules:

$$\omega_{ref} = \begin{cases} 2\beta_{max}q & \text{if } 0 < q < q_f \\ -2\beta_{max}(-q) & \text{if } q_f < q < 0 \\ \omega_{max} & \text{if } q_f < q < q_{max} \\ -\omega_{max} & \text{if } -q_{max} < q < -q_f \end{cases}$$
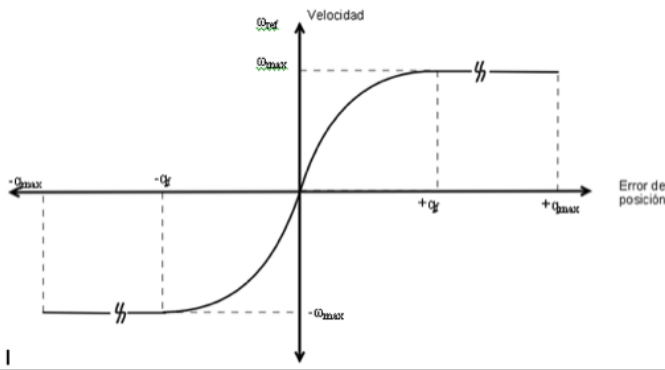
Fig. 4.   Position errors and speed commands relation

Fig. 5.   Speed IP controller

where

q_f Error from the deceleration reginon starts (It defines directly the breaking duration).

ω_{ref} Speed value wanted.

B_{max} Digital value representing the maximum deceleration used.

q_{max} Maximum position error.

figure 4 shows these rules graphically.

IV. SPEED AND POSITION MEASUREMENT

The rotor position is determined capturing, using the microcontroller quadrature interface (QEI), the pulses train of the encoder mounted on the motor shaft. The input of the microcontroller QEA captures the encoder channel A, input QEB captures the encoder channel B, and the input IDX the index. Both channels are captured in quadrature A and B to detect movement as well as direction. Inputs QEA and QEB generate a pulses count for the up-transition as well as those down from pulses A and B. In this way 1024 puss can be detected per turn with the 256 slots encoder. Input IDX generates an interruption only in the down transition of the index signal. This signal is used to perform an adjust of the position at the end of each turn to rectify errors in the detection of the channel A and B pulses. To detect the movement direction, on each sample interruption routine the pulses of the channels A and B are read. Because they are out of phase for a quarter of cycle, the microcontroller quadrature interface has a turn direction detection bit which is read at the moment where the timer interruption is generated. The speed is calculated based on the pulses train coming from the encoder, taking into account, additionally, the sampling period used to read the channels. In this period the pulse counter is read, in the net sample it is read again and it is subtracted the first reading.

V. SERVOMECHANISM MODEL IDENTIFICATION

For the speed controller a Digital Integral-Proportional (IP) controller was implemented. The analogical [12] version of the speed control loop is shown in Figure 5.

In this diagram, $G_p(s)$ includes the CD-CD converter, el CD motor and the mechanical system.

To design the gain of the digital IP controller it is required to know the Gp(s) mathematical model. We now briefly describe the model for $G_p(s)$ used and the method used for its estimation. The CD motor transfer function with a vol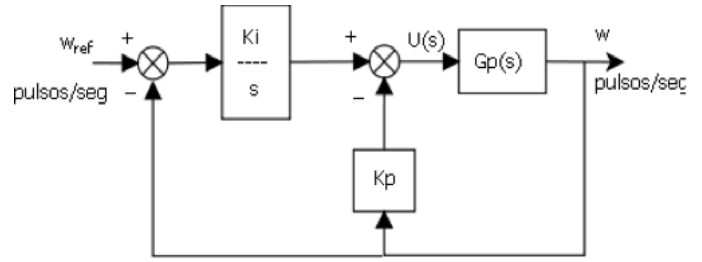tage input and a speed output, normally is approximated with a second order model. However, because the motor electric time constant is much smaller than its mechanical constant, a first order approximation can be used for the speed controller design. Therefore, $G_p(s)$ can be represented using equation 3.

$$G_p(s) = \frac{\omega(s)}{U(S)} = \frac{A}{\tau s + 1} \quad (3)$$

where: ω is the angular speed in pulses/sec. U es el digital speed command sent by the microcontroller. a is the CD motor gain (final value which is close to the unitary step). τ is the time constant for Gp(s).

This model was estimated for each servomechanism applying a step input (digital command $u = 70$ constant) to $G_p(s)$ for each axiis$X$, Y, y Z, capturing the speed output (in $pulses/sec$) and comparing the obtained response ω vs t with the response of $G_p(s)$ to a step input as indicate in equation 4 [13].

$$\omega(t) = Au[1 - e^{-\frac{t}{\tau}}] \quad (4)$$

VI. SPEED CONTROL DESIGN

The close loop transfer function of the speed control system in figure 5, with the first order approximation of $G_p(s)$ is given by 5.

$$G_p(s) = \frac{\omega(s)}{\omega_{ref}(s)} = \frac{\frac{K_i A}{\tau}}{s^2 + \frac{1 + K_p A}{\tau}s + \frac{K_i A}{\tau}} \quad (5)$$

Which in its digital form takes the form 6 [14]:

$$G(z) = \frac{A_1 K_{id}}{z^2 + [A_1(K_{pd} + K_{id}) - R - 1]z + [R - A_1 K_{pd}]} \quad (6)$$

where:

K_i Analogical integral gain.

K_p Analogical proportional gain.

T Sampling period

$R = R(T)$ $e^{\frac{-T}{\tau}}$

$A_1 = A_1(T)$ $A[1 - R(T)]$

$K_{id} = K_i T$ Digital gain

K_{pd} $K_p - \frac{1}{2}K_{id}$

Comparing eanalogic model equation 5 with the second order generalized system transfer function, we obtain 7 y 8.

$$K_i = \frac{\omega_n^2 \tau}{A} \quad (7)$$

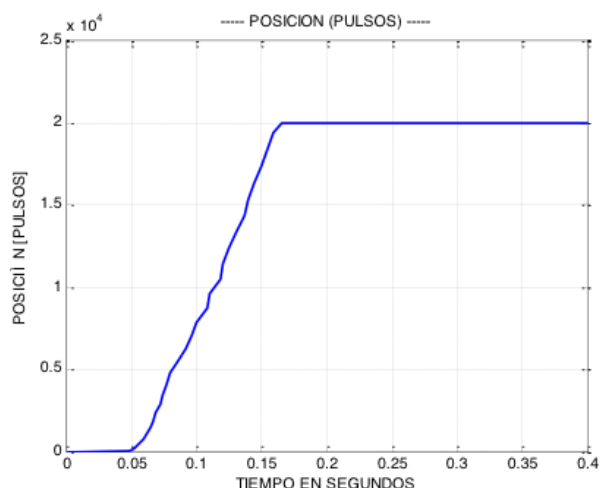$$K_i = \frac{2\xi\omega_n\tau - 1}{A} \quad (8)$$

Fig. 6.   Step position command closed loop response

Fig. 7.   Speed control performance

Fig. 8.   Complete manipulator system

Fig. 9.   Figure drawn in the computer user interface.

donde:

ξ Damping factor.

ω_n System natural frequency.

In this way the analogical gains K_i y K_p and the digital gains K_{id} y K_{pd}, can be calculated selecting the values for ξ and ω_n which provide the closed loop control system wanted behaviourque proporcionan el comportamiento deseado del sistema de control de lazo cerrado. To select this values, the equations which define the maximum over-impulse and the time to establish a second order sub-damped system

VII.   EXPERIMENTAL RESULTS

Firstly, all the designed hardware components such as the CD-CD converters tablets and microcontroler interfaces were tested. Then the software modules were tested in the following order: speed control and position of each of the servomotors, the communication software between the master and the computer as well as the slaves, the interface software as well as the computation of the positions and velocities by the computer. Finally, the tests of the manipulator as a lettering tool are realized.

A good control of the servomechanisms is the key factor to assess how useful the manipulator will be. Because of that, special attention has deserved the assessment of the position and speed controllers designed for each servomechanism. Figure 6 shows the servomechanism axis X response in closed loop to a setp position command of 32,767 pulses.

Tha graph shows good performance of the servomechanism with minimal over-impulse. Figure 7 presents the speed controller response corresponding to the change of position in Figure 6 We can see the speed adjusts itself to the profile wanted shown in figure 3. The same happens with the other axis. These responses were obtained through the serial port with a GUI developed with LabView.

To test the manipulator as a letterer, several figures were traced and executed using the the computer user interface Figure 8 shows the complete manipulator system. Figura 9 shows the drawing made using the Matlab GUI [7] with the computer, while Figura 10 we can see the dragan lettered on the wooden surface, which is identical to the one in the computer. The capacity of the manipulator system allows to make traces using continuos por separated unes, as is the
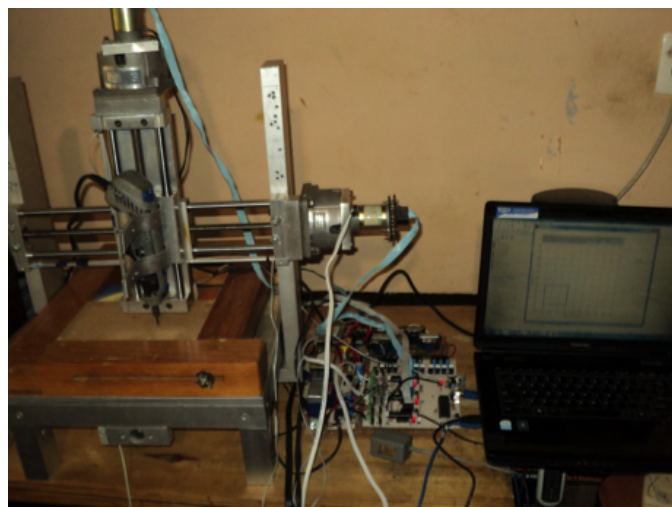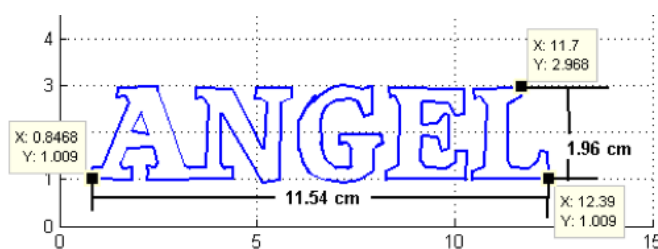
case of the first two letters and the last three respectively in Figure . The lettering was succesfully used on two different kind of surfaces: MDF and pine wood, using 1/32" router tips. The precision of the manipulator depends of the router tip used as its resolution is 3.9×10^{-8}m.

VIII.   FINAL REMARKS

This document has presented the design of a manipulator control with two freedom degrees based on PIC microcontrollers, used as letters to draw figures onto wooden surfaces. The details of the hardware and software developed were presented. Special algorithms were included to control the position of each of the servomechanisms included in the manipulator. In this algorithm, the controllers generate

Fig. 10.   Figure letterer onto a wodden surface.

speed commands which depend on the position error. The algorithms developed for the position and speed control provided a good precision. The document describes also the design of a speed digital IP control, including the applied method to estimate the model of each servomechanism. The estimated model includes a DC-DC electronic converter , the CD Motor as well as the mechanical system. The tests assessed to each servomechanism have shown the effectivity of the design here presented.

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