

M. Topalbekiroğlu,
*L. C. Dülger,
A. Kireççi

Positioning Mechanism in a Knotting System: A Case Study

University of Gaziantep,
Faculty of Engineering
Department of Textile Engineering

*Department of Mechanical Engineering
Gaziantep, Turkey

Abstract

A positioning mechanism driven by a stepper motor in a knotting system forming a Turkish knot is presented herein. A prototype carpet loom was designed to include the positioning mechanism in the experimental system. A mathematical model describing the dynamic characteristics of the positioning mechanism-stepper motor configuration was developed. Simulation studies were carried out together with experiments on the positioning mechanism. The simulation results are reported herein with experimental verification.

Key words: knotting system, stepper motor, positioning mechanism, mathematical modelling, Turkish knot.

The rotor of a stepper motor accelerates rapidly to reach the new step position. Stepper motors are ideal for a digitally based control system. These motors can be used for industrial, military, or medical purposes when there is a requirement for stepping from one position to another. Positioning, timing, and synchronised actuation can be given as example applications. Their construction is very simple, introducing no brush-gear with the moving part i.e. the rotor. Accurate positioning and speed control can be achieved in an open loop system by eliminating feedback transducers; hence the positional error is non-cumulative. Stepper motors can be classified by looking at the type of rotor as variable reluctance (VR), permanent magnet (PM) or hybrid. The driver mode selected can be full-step, half-step or micro stepping. The system performance i.e. the step accuracy and resolution can be increased by micro stepping. Thus even smaller steps can be obtained by using different currents through the two motor windings [1 - 6].

Some related work on the modelling and motion control of stepper motors was found. Jufer [7] established selection criteria for drive by stepper and dc motors by looking at the characteristics of incremental motion with a small number of steps and displacement with a great number of

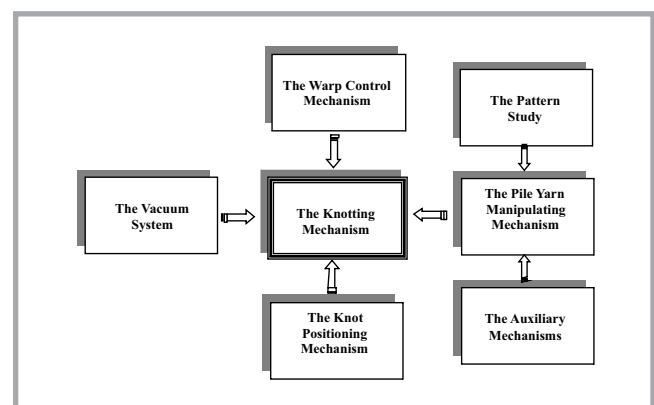
steps. Jones et al [8] performed optimal control of a voltage driven stepper motor with an inertia load. Zribi et al [9] considered the position control of a permanent magnet stepper motor using the exact linearisation method. Bodson et al [10] considered the high-performance nonlinear feedback control of a permanent magnet stepper motor. A model-based control law was developed using exact linearisation methodology and implemented on an experimental set-up, in which a linear positioning table was used. Hung [11] later studied torque ripple minimisation for variable reluctance motors. Lyshevski [12] considered the motion control of electromechanical servo-devices with permanent magnet stepper motors. The complete nonlinear dynamics of permanent magnet stepper motors was used.

In this study, a prototype carpet loom was designed and constructed to produce knots for handmade carpets electromechanically. Handmade carpets have two forms known as Turkish and Persian knots, whose structures are more complex than that of machine carpets [13]. The prototype has many mechanisms such as the positioning mechanism, warp control mechanism, holding mechanism and others. Here only the positioning mechanism on this prototype is presented with details thereof. An experimental

Introduction

Traditionally dc motors are used in positioning systems to ease their control during acceleration and deceleration. During repetitive motion, excessive mechanical wear occurs and performance loss is seen. A positioning mechanism can be implemented using stepper motors which operate open-loops in any step position converting information in digital form to an output shaft motion. Successive energising and de-energising phases on the motor give an incremental motion.

Figure 1. Flow diagram of the knotting system.



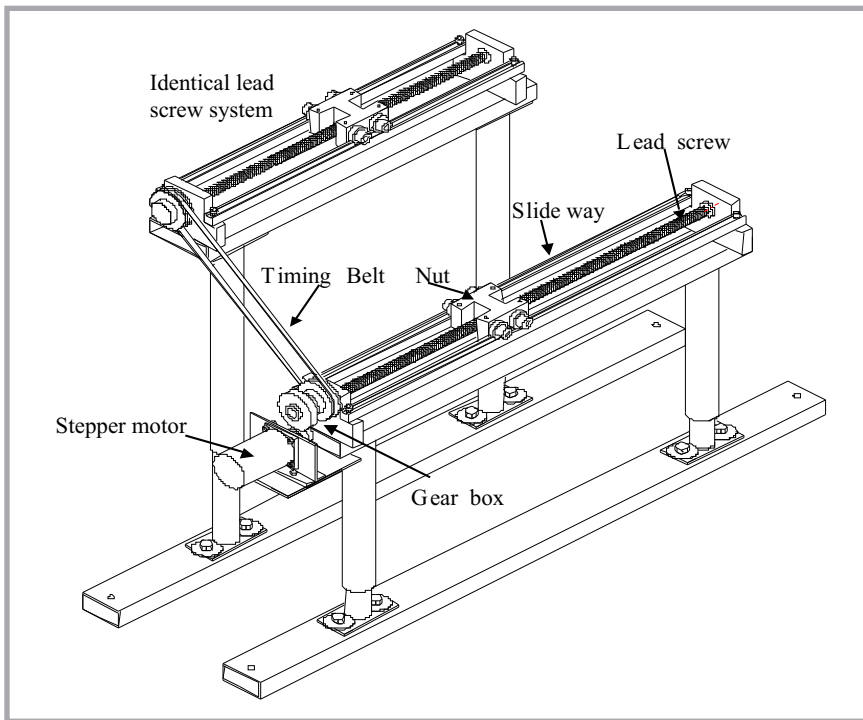


Figure 2. Positioning mechanism.

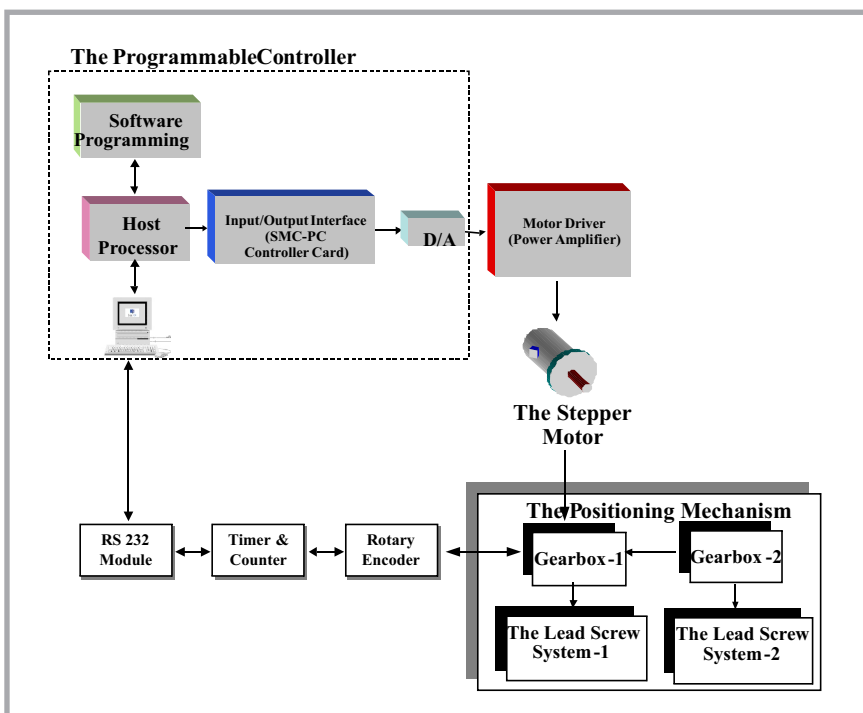


Figure 3. Motor control diagrams in the knotting system.

system for the positioning mechanism is introduced. A theoretical nonlinear model is also developed for the stepper motor-positioning mechanism system to understand its dynamic response. Motion control and implementation issues of stepper motors are presented. Simulation results are verified for a positioning mechanism in a knotting system driven by a hybrid stepper motor.

■ The positioning mechanism

The knotting system is a composition of several independent mechanisms in order to practically form Turkish knots. The design problem of such a system can be solved by separating it into sub problems. The function of the system and its decomposition can be considered as the main steps for the design of the knotting

system. Then the optimum subsystems, assemblies and components are developed to provide these functions. The flow diagram of the knotting system consists of the following mechanisms: the knotting mechanism with a vacuum unit, the warp control mechanism, the pile yarn manipulating mechanism with a pattern study, the auxiliary mechanisms (the holding mechanism and cutting mechanism) and the knot positioning mechanism, which are shown in *Figure 1* (see page 59) [13 - 15].

The pile yarn manipulating mechanism performs the function of supplying coloured of pile yarn, connecting the pattern to the knotting mechanism, meanwhile one end of the pile yarn can be kept by the pile yarn holding mechanism [13 - 15]. The warp control mechanism serves to prepare a pair of warp yarns by distinguishing it from other pairs, separating this pair from others by a certain distance according to the knot type. The knotting mechanism then holds the pile yarn using the vacuum system; at the same time the cutting mechanism cuts off the pile yarn at the end. Finally, the knotting mechanism forms the knot. The knot positioning mechanism then places the knot by pulling down the tips of the pile yarn.

Details of the positioning mechanism

The positioning mechanism is required to move the knotting system forwards and backwards in the width direction of the carpet, as shown in *Figure 2*. This mechanism coordinates the knotting system with respect to each warp yarn. A hybrid type of stepper motor is used to drive the positioning mechanism in the knotting system. This motor has a step angle of 1.8° , is 2-phase with four wound poles on the stator and has 200 steps/revolutions. The specifications of the stepper motor are given in *Table 1*.

The positioning mechanism is used to carry a table in the width direction of the frame by converting rotational input to translation. Several elements are included: stepper motors, two lead screws, two nuts, two sideways, a table and coupling units between the stepper motors and lead screws. One of the coupling units is fixed between the stepper motor and lead screw 1. The other is fixed between two parallel lead screw shafts, giving a reduction of 2:1. The parameters of the motors are easily obtained from the manufacturers. Position coordination between the

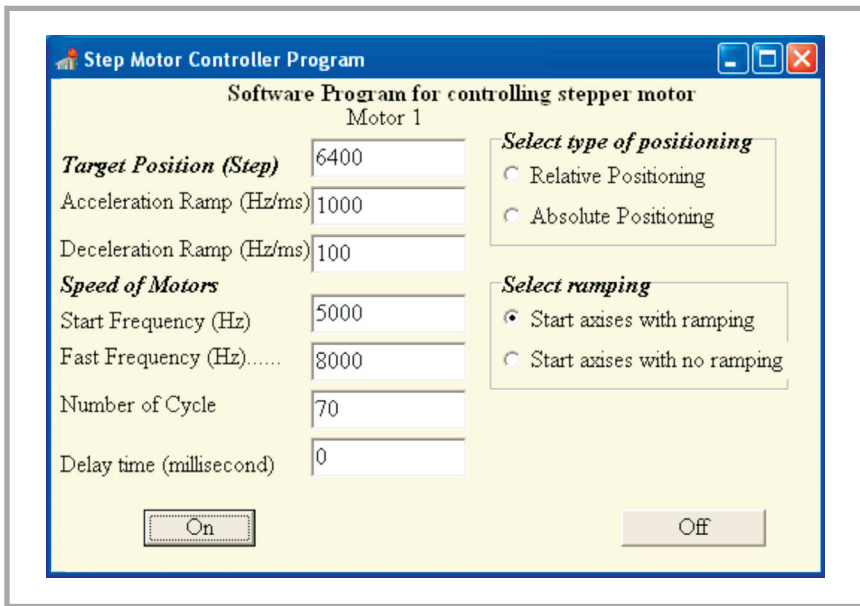


Figure 4. Image of stepper motor control software.

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} -R/L & 0 & 0 & K_m/L \sin(N_r x_3) \\ 0 & -R/L & 0 & K_m/L \cos(N_r x_3) \\ 0 & 0 & 1/J & 0 \\ -K_m/J \sin(N_r x_3) & -K_m/J \cos(N_r x_3) & 0 & -B/J \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 1/L & 0 \\ 0 & 1/L \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_A \\ V_B \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ -1/J \end{bmatrix} T_L \quad (5)$$

Equations 5.

two lead screw systems is provided by a timing belt.

Stepper motor control system

The stepper motor control system consists of a stepper motor drive (SMC 88 Constant Current Driver), a PC (400 MHz, 64 MB RAM, and 9 GB Hard disk), a stepper motor controller (SMC-PC module), and Nanotech 1.8° - 2 phase stepper motors. A block diagram of the stepper motor control system used in the positioning mechanism is given in Figure 3. The basic structure of the programmable controller is given in the form of a dashed box in the same figure.

The programmable controller consists of a PC, I/O interface card, a controller module and software. The controller module converts digital information of the position (step number) and direction (CW or CCW) of the stepper motor into electrical signals in the range of ± 10V. The controller manages the other control functions, including acceleration, deceleration, steps per second and distances necessary for applications. Com-

munication to the controller is performed by either a Bus-Based or through an RS 232/ RS422 serial port. A motor controller card is inserted into slots accessible on computer expansion boards [13, 16].

The controller card overlays only one of the computer's I/O addresses and is capable of controlling up to four motor axes. Software was developed (Delphi) to run the motor, depending on the application required. When the program is executed, the stepper motor adjusts the location of the positioning mechanism, which carries all the mechanisms to form a Turkish knot. In the full step mode, 200 step pulses complete one revolution. With transmission elements, 1600 steps are generated with each revolution. One knot is performed in four revolutions with 6400 steps. The software manages the other control functions, such as the acceleration, deceleration, steps per second and distances necessary for applications. The software controlling the system is similar to that in Figure 4, when the motor control program is executed.

Mathematical model

The knotting system consists of several independent mechanisms to produce a Turkish knot. Accurate positioning of all the mechanisms during the knotting process is vital [13]. Systems of ordinary differential equations are obtained to represent the behaviour of a step motor under all operating conditions. By looking at the fundamental laws involved: the law of electrical circuits, Newton's laws etc., a mathematical model is derived. A complete mathematical model of a stepper motor consists of differential equations for the current and dynamic equations for the rotor [1, 2, 11, and 17]. Two sources of magnetic field, stator windings and a permanent magnet are used in hybrid stepper motors.

Voltage equations for the phase windings of a two phase hybrid stepper motor may be written as,

$$L \frac{di_A}{dt} + Ri_A - K_m w \sin(N_r \theta) = V_A \quad (1)$$

$$L \frac{di_B}{dt} + Ri_B + K_m w \cos(N_r \theta) = V_B \quad (2)$$

and equation 3,

$$J \frac{dw}{dt} + Bw = -K_m i_A \sin(N_r \theta) + K_m i_B \cos(N_r \theta) - T_L \quad (3)$$

where:

- V_A, V_B - voltages in phases A and B in V,
- i_A, i_B - currents in phases A and B in A,
- L - inductance of the phase winding in H,
- R - resistance of the phase winding in Ω ,

Table 1. Specifications of the stepper motor.

Step angle	1.8°
Phase	2
Voltage	12 V DC
Current/winding	0.94 A
Resistance/winding	12.8 Ω
Inductance/winding	95 mH
Rotor inertia	3.5x10 ⁻⁵ kg/m ²
Weight	1.4 kg

Table 2. Parameters for the motor and positioning mechanism.

$J_r = 3.5 \times 10^{-5}$ kg/m ²	$J_{s1} = 8.04 \times 10^{-7}$ kg m ²
$J_{s2} = 12 \times 10^{-7}$ kg m ²	$R = 12.8 \Omega$
$L = 95$ mH	$V_A = V_B = 12$ Volt
$M_1 = 0.35$ kg	$M_2 = 6.0$ kg
$P = 2$ mm	$N = 2$
$N_r = 50$	

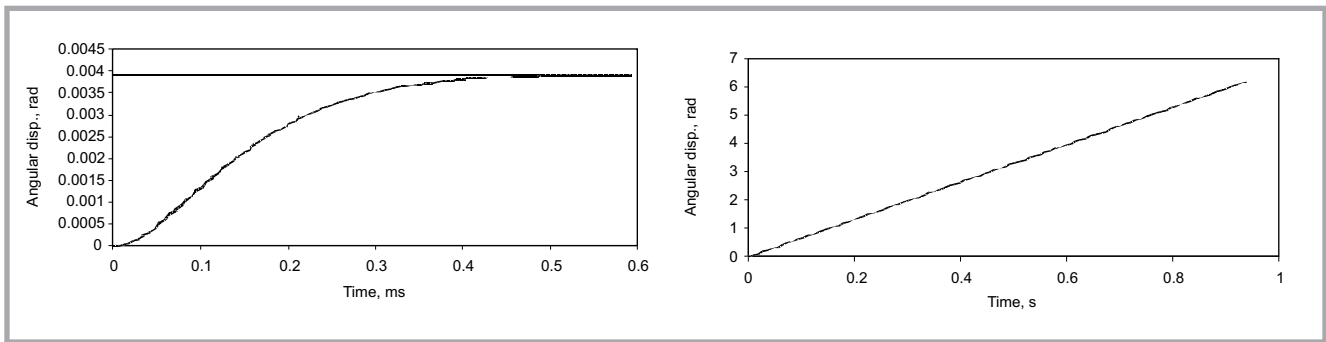


Figure 5. Simulation results; (a) single step, (b) one revolution.

- B - viscous friction coefficient,
- J - equivalent moment of inertia in $\text{kg}\cdot\text{m}^2$,
- N_r - number of rotor teeth,
- K_m - motor torque constant in Nm/A .
- $\theta, \omega, \frac{d\omega}{dt}$ angular displacement, velocity and acceleration of the rotor.
- T_L - load torque in Nm .

And equation 3a

$$J = J_r + \left(\frac{J_{s1}}{N^2} + \frac{J_{s2}}{N^2} \right) + M_1 \left(\frac{P}{2\pi} \right)^2 \cdot \frac{1}{N^2} + M_2 \left(\frac{P}{2\pi} \right)^2 \cdot \frac{1}{N^2} \quad (3a)$$

where:

- J_{s1}, J_{s2} - moment of inertias of leadscrews 1 and 2 in $\text{kg}\cdot\text{m}^2$,
 - N - reduction ratio
 - M_1, M_2 - translating masses in kg
 - P - pitch of the leadscrews in m .
- And

$$x_{L1} = x_{L2} = \left(\frac{P}{2\pi} \right) \frac{1}{N} \theta \quad (4)$$

where:

- x_{L1}, x_{L2} - linear displacements of **Table 1 & 2** in m .

State Space Model of the Knotting System

The state space model of the stepper motor and knotting system is described by taking i_A, i_B, θ and ω as the states. Equations (1) and (3) represent the electrical and dynamic equations for the knotting system with a motor. The state variables are x_1, x_2, x_3 and x_4 , represented as

$x = [i_a, i_b, \theta, \omega] = [x_1, x_2, x_3, x_4]$. Hence, converting equations (1) to (3) in the state space model, the following equations are obtained.

State equations can be given in a vector-matrix form as $\dot{x} = Ax + Bu$, it is presented in Equation 5.

There are five sets of inputs: a matrix, initial values of the state variables, a B matrix, the input variables, the step length and the total time required, which are given in the following section.

Numerical results

The dynamic response of the motor is then found by computer simulation. In the previous section, a state space model was derived for this electromechanical system. A numerical method of integration is then used to solve the differential equations. The control scheme includes many details: the input voltages to the windings and the duration of the process, depending on the number of knots required. The parameters for the motor

and positioning mechanism are given in **Table 2**.

Equations (1) to (3), representing the system dynamics, are of the nonlinear differential type; they should be given in the form of a system of 1st order differential equations performing differentiation. Equations (1) (2) are 1st order differential equations for a motor electrical structure, and equation (3) gives the dynamic equation according to Newton's second law. Therefore it is to be converted into two first order equations to carry out integration in a vector matrix form. The system given by equation (5) consists of four 1st order nonlinear equations, which are simulated using the Runge-Kutta numerical integration routine.

The inputs to the model are phase voltages V_A & V_B , the initial conditions for the currents i_A & i_B , and the initial condi-

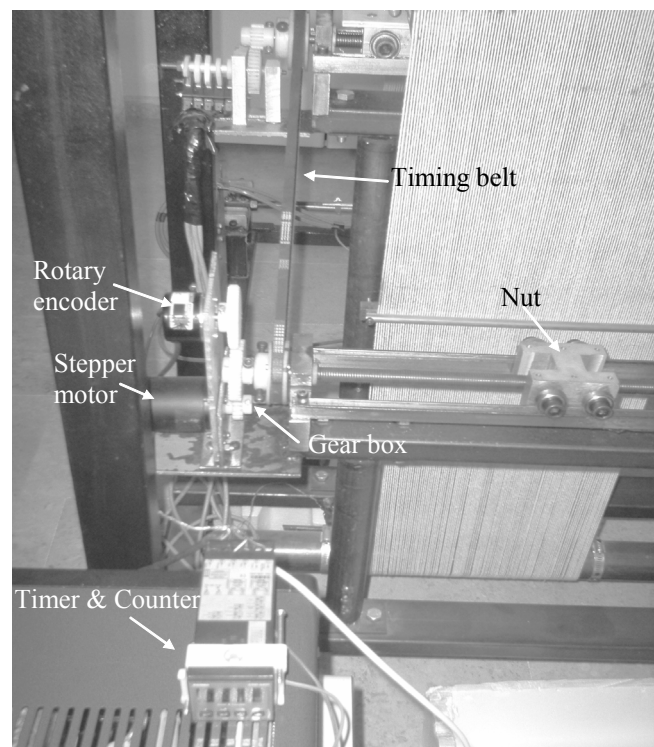


Figure 6. Photograph of the experimental set up.

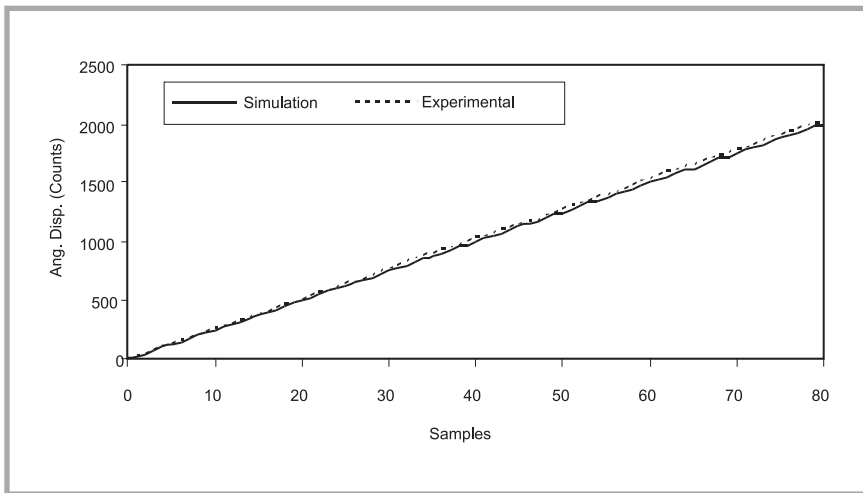


Figure 7. Experimental and Simulation Results.

tions for the rotor position and velocity. The rotor variables θ and ω are obtained from the dynamic equation of the rotor. In this system one Turkish knot is performed in 3.8 seconds. It is possible to get higher speeds by altering frequency values in the control software. Neglecting frictional losses in the mathematical model, the response is observed for a period of 0.95 seconds.

Plots corresponding to the motor position versus time are given in Figure 5. In the model the variables are scaled as radians and time. Figure 5.a shows simulation results of the motor for a single step at 0.6 ms, and Figure 5.b shows one revolution of the motor and load after 0.95 seconds (1600 steps).

Experimental results

Figure 6 shows a photograph of the experimental setup. An optical encoder (1000 ppr) is attached to the table to obtain positional measurements of the motor and table. One knot is performed every 2000 counts. When calculating the linear displacements of slide ways 1 and 2, equation (4) is used. Hence each movement amounts to 4 mm on the table. When 70 knots are performed, a linear movement of 280 mm occurs, after which the table returns to its original position. Figure 7 shows experimental and simulation results. Here the output is given in encoder counts and samples corresponding to the motion cycle. There is a good match between the model and experimental response of the motor, as expected.

Conclusions

This study was a part of a project (DPT-State Planning Organisation of Turkey, Grant No: 97K 121210) in which the design and construction of a prototype was performed to produce handmade carpets mechanically. There are other mechanisms to produce the Turkish knot in a real system. The synchronisation of different mechanisms (Figure 1) presents the most difficult part. This system is already in operation and performs a knot successfully. A study of this is given in detail in [13, 14]. Some studies are currently being conducted on the complete synthesis of mechanisms involved in the knotting system.

A positioning mechanism is proposed for the knotting system with stepper motors so that a handmade carpet loom can specifically produce Turkish knots. The positioning mechanism is used to convert the rotational motion in the knotting system to translational motion. The mathematical model of a step motor connected to a positioning mechanism is derived from the knotting system. There was no problem deriving system equations with related actuator dynamics. Stepper motor dynamics is studied by simulation. Some experimental studies are also being carried out with respect to the system. Consequently, many experiments on the positioning mechanism built were performed at different speeds in the knotting system. Experimental measurements were taken for the prototype. Some practical problems were experienced during measurements. Some of the problems were caused by the mechanical construction. They can be partially eliminated by properly aligning the shafts and gears in

the construction. The complete operation of the system is then obtained.

References

1. Krause Paul C., Wasynczuk Oleg, 'Electromechanical Motion Devices', McGraw Hill, 1989.
2. Kenjo Takashi, Sugawara Akira, 'Stepping Motors and their microprocessor controls', Oxford University Press, 1994.
3. Ong Chee-Mun, 'Dynamic Simulation of Electric Machinery Using MATLAB/SIMULINK', Prentice Hall, 1998.
4. Bailey S.J., 'Steppers and servomotors offer designers rich motion control options', Control Engineering, Vol.35, no.5, pp. 81-85,1998.
5. Acarnley P.P., 'Stepping Motors: A guide to modern theory and practice', Peter Peregrinus Ltd., 1984.
6. Huntingford John R., 'Choosing and using Stepper motors', New Electronics, Vol.20, No.2, p 87-89,1987.
7. Jufer M., 'Selection criteria of drive by stepping and DC motors', Electromechanical and Electrical Machines Laboratory, Swiss Federal Inst. of Tech., pp. 13-19.
8. Jones D.I., Finch J.W., 'Optimal control of a voltage driven stepping motor', IEE Proceedings, Vol. 130, No.4, pp.175-182,1983.
9. Zribi M., Chiasson J., 'Position control of PM stepper motor by Exact Linearization', IEEE Transactions on Automatic Control, Vol.36, No.5, p620-625, 1991.
10. Bodson M., Chiasson John N., Novotnak R., 'High-Performance nonlinear feedback control of a permanent magnet stepper motor', IEEE Transactions on Control Systems Technology, Vol.1, No.1., pp 5-14,1993.
11. Hung John y., 'Torque ripple minimization for variable reluctance motors', Mechatronics, Vol.4, No.8, pp.785-798, 1994.
12. Lyshevski S.E., 'Motion control of electromechanical servo-devices with permanent-magnet stepper motors', Mechatronics, Vol.7, No.6, pp.521-536, 1997.
13. Topalbekiroğlu Mehmet, 'Design, Construction and Control of Computer controlled Knotting System', Ph.D Thesis, University of Gaziantep, July 2002.
14. Topalbekiroğlu M., Kirecci A., Dulger L.C., 'A study of weaving Turkish Knots in handmade carpets with an electromechanical system', Proc. IMechE Vol.219 Part I: J. Systems and Control Engineering, pp.343-347, 2005.
15. Topalbekiroğlu M., Kirecci A., Dulger L.C., 'Design of a pile-yarn manipulating mechanism', Proc. IMechE Vol.219 Part B: J. Engineering Manufacture, pp.539-545, 2005.
16. PP Electronic GmbH, 'Manual for SMC-PC', Germany
17. Kuo B.C., 'Theory and Application of Stepper Motors', Dept of Electrical Engineering, University of Illinois, Urbana-Champaign.

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