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Mathematical Model of a Mechatronic Pinch-Type Gripper for Textiles

Abstract
In this paper, the dynamics of a pinch-type gripper for textiles have been studied. We considered an example of a gripper in which the motion of closing and opening is effected by means of a screw. A set of equations describing the gripper's behaviour, preceded with a differential equation of the driving torque of the gripper's driving motor, has been solved numerically using the Runge-Kutta method. The computer program which controls the gripper operation includes feedback between the reaction force of the textile material and the supply voltage. The results of calculations which illustrate the textile material's reaction to the gripper's action are presented in diagrams.

Key words: *gripper for textiles, computer control, mathematical model, garment production, robotisation.*

Introduction. Brief Review of Grippers for Textiles

Robotising the garment industry [1] requires the development of grippers which, when attached to a manipulator, could perform operations such as taking a garment section from the stack, folding it and aligning the edges of the pieces to be sewn together. Many different devices serving this purposes have been designed. Most of them increase the efficiency and quality of work. A brief review of gripper devices designed and described in the 1980s and 1990s is given below.

In one of these solutions [2], a fabric is lifted by means of four fingers, each of which is made up of four parts. The opened fingers are applied to a fabric and then closed, resulting in 'pinching' it. The fingers are reeved through the orifices in three plates joined by means of a shaft. When the last movable plate is slid over the fingers of an appropriate shape, the fingers close.

In another solution [3], a piston in which a rod moves is fastened to two immovable plates. At the lower end of the rod is a frame with two shafts that can spin on their own axes. Two appropriately-shaped levers are mounted on these shafts. On their lower ends are jaws positioned in parallel to them, while their upper ends are fastened to the lower immovable plate. When the shaft is slid into the piston, the movable frame approaches the immovable plate, while the jaws open by means of the lever. On the other hand, when the shaft slides out, the jaws close. The layer of fabric is seized at the stage of closing the jaws.

Another interesting solution [4] is an idea to shape the arms' endings with crossed catching jaws so that they contain one spring coil each and special wedges. A movable plate with two fingers approaches the wedges and exerts pressure on them. As a result, the arms of the clamp bend in the spring coils and the jaws open. As soon as the pressure on the wedges is relieved, the jaws close and take the fabric. The end of one jaw is sharp while the other is blunt, which additionally facilitates catching the fabric.

A different idea [5] is to catch the fabric by means of small teeth on a wheel. When the wheel turns, it takes the first layer off the pile and sticks it into the pocket of a slipper interacting with the wheel. A special finger holds the whole pack during the fabric transport.

A further solution [6] patented in 1998 is based on raising a woven fabric by means of two clamps, which approach each other as they touch the fabric of the upper layer and seize its protrusion in relation to the stack. One of the clamps is mounted on the bottom end of a holder

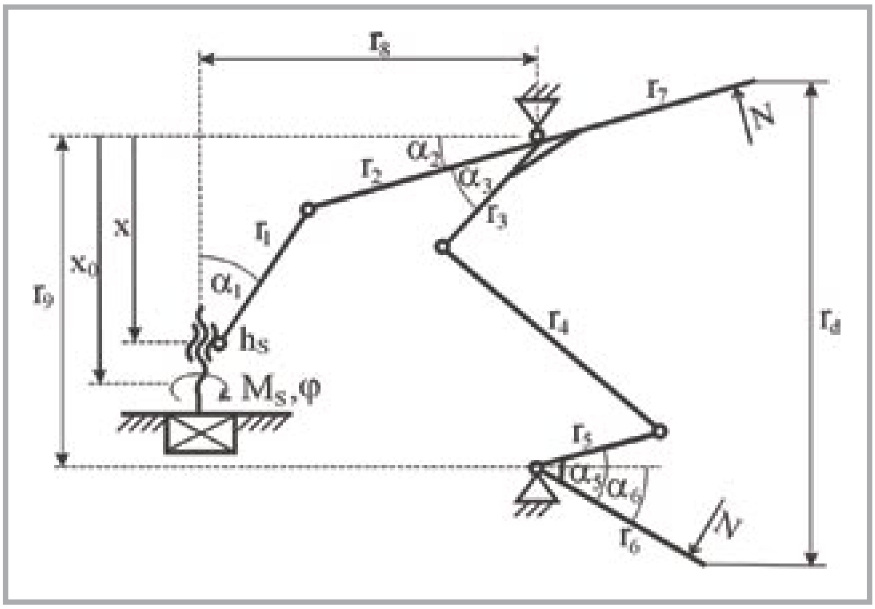

***Figure 1.** Plan of the gripper; M_s - motor driving moment, φ - rotation angle of the main shaft, h_s - screw pinch, $r_1 ... r_7$ - lengths of the gripper elements, r_8, r_9 - distances between non-movable points of the device, α_1, α_2, α_6 - angles between a given gripper element and the horizontal or vertical axis, α_3, α_5 - angles of constant value between given elements of the gripper, N - force compressing the material, x_0 - initial position of the gripper, x - position of the gripper at a given time, r_d - distance between the fingers at a given moment.*

arm, whereas the other on the frame. The closing of the gripper and catching the fabric takes place at the point when a pneumatic cylinder is set in motion; pushing the wedge block, which slides between two roller guides in the direction of the frame, causes (through the slide of the spring) one of the clamps to approach the other. When the clamps open and allow the fabric to fall, it can be noted that a rod is arranged below the gripping device which helps in the complete unfolding of the fabric.

Another gripper example [7] is based on a construction where the contact with the upper part of the fabric is performed by means of an arm moving a device which serves for sampling the fabric. When this device is displaced down and touches the fabric, its clamps rotate around the device's axis to a position allowing the fabric element to be compressed, pierced, and held by use of the edges of needles mounted to the clamps. During this action, a mobile rod is moved up to this position in which the spring mechanism brings the clamps to a standstill in the closed position. The clamps' movement to the opening position causes the release of the fabric. The whole device is driven by an electric motor.

An interesting solution is presented in [8]. Needles embedded slantwise in two grips, which in turn are mounted on a frame with the use of two shafts with springs, are used as elements for separating the woven fabric from the stack's upper layer. The sampling of the fabric element takes place when the frame with the protruded needles is pushed onto the woven fabric, and allows the needle edges to pierce the fabric. Next, the grips are displaced at a distance of a few millimetres, and the whole frame is raised together with the upper layer of the fabric to separate it from the stack.

An attempt was also made to strictly imitate a human hand [9]. Two fingers, similarly to the hand's fingers, grasp the edge of the fabric. The device has a gauge for determining the stack's height. The construction of this robot allows the fabric to be raised from the stack, transferred to the desired place, and laid in an appropriate manner.

All the designs discussed above are insufficient to perform the work done by human hands, and further studies should be conducted. A classification of grippers can be found in paper [10].

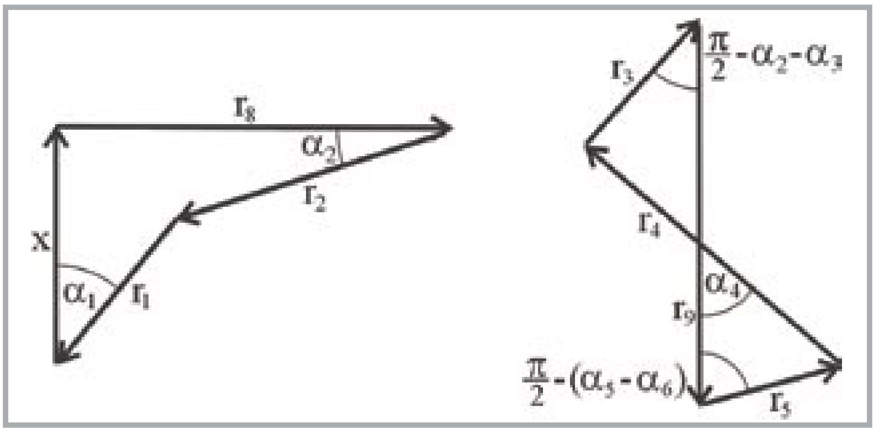

Figure 2. *Closed vector polygons, representative of the gripper device presented in Figure1.*

$$
\begin{aligned}
&x = x_0 - \frac{\varphi}{2\pi} h_s \\
&F_1 = r_8 - r_2 \cos\alpha_2 - \sin\alpha_1 = 0 \\
&F_2 = x - r_2 \sin\alpha_2 - r_1 \cos\alpha_1 = 0 \\
&F_3 = r_5 \sin(\pi/2 - (\alpha_5 - \alpha_6)) - r_4 \sin\alpha_4 + r_3 \sin(\pi/2 - \alpha_2 - \alpha_3) = 0 \\
&F_4 = r_5 \cos(\pi/2 - (\alpha_5 - \alpha_6)) - r_4 \cos\alpha_4 + r_3 \cos(\pi/2 - \alpha_2 - \alpha_3) - r_9 = 0
\end{aligned} \tag{1}
$$

$$
M_s - I_s \frac{d^2\varphi}{dt^2} - I_7 \frac{d^2\alpha_2}{dt^2}\frac{d\alpha_2}{d\varphi} + N \frac{d\alpha_2}{d\varphi} r_7 - I_6 \frac{d^2\alpha_6}{dt^2}\frac{d\alpha_6}{d\varphi} + N \frac{d\alpha_6}{d\varphi} r_6 = 0 \tag{3}
$$

$$
\frac{d\alpha}{dt} = \frac{d\alpha}{d\varphi}\frac{d\varphi}{dt}, \quad \frac{d^2\alpha}{dt^2} = \frac{d^2\varphi}{dt^2}\frac{d\alpha}{d\varphi} + \left(\frac{d\varphi}{dt}\right)^2 \frac{d^2\alpha}{d\varphi^2} \tag{9}
$$

$$
\begin{aligned}
&\left[I_s + I_7\left(\frac{d\alpha_2}{d\varphi}\right)^2 + I_6\left(\frac{d\alpha_6}{d\varphi}\right)^2\right]\frac{d^2\varphi}{dt^2} + \left[I_7 \frac{d^2\alpha_2}{d\varphi^2}\frac{d\alpha_2}{d\varphi} + I_6 \frac{d^2\alpha_6}{d\varphi^2}\frac{d\alpha_6}{d\varphi}\right]\left(\frac{d\varphi}{dt}\right)^2 + \\
&-N\left(r_7 \frac{d\alpha_2}{d\varphi} + r_6 \frac{d\alpha_6}{d\varphi}\right) - M_s = 0
\end{aligned} \tag{10}
$$

$$
\begin{aligned}
&\frac{d\varphi_1}{dt} = \varphi_2 \\
&\frac{d\varphi_2}{dt} = \frac{M_s + N\left(r_7 \frac{d\alpha_2}{d\varphi_1} + r_6 \frac{d\alpha_6}{d\varphi_1}\right) - \left[I_7 \frac{d^2\alpha_2}{d\varphi_1^2}\frac{d\alpha_2}{d\varphi_1} + I_6 \frac{d^2\alpha_6}{d\varphi_1^2}\frac{d\alpha_6}{d\varphi_1}\right]\left(\frac{d\varphi_1}{dt}\right)^2}{I_s + I_7\left(\frac{d\alpha_2}{d\varphi_1}\right)^2 + I_6\left(\frac{d\alpha_6}{d\varphi_1}\right)^2}
\end{aligned} \tag{11}
$$

Equations 1, 3, 9-11

The magnitude of the force exerted by those grippers is not controlled, and can damage the fabric. The purpose of this paper is to study a gripper with computer-controlled force.

Pinch-type Gripper

The gripper analysed is presented in Figure 1. It is driven with the use of an electric motor by means of a screw with the pitch h_s. The screw moves the gripper elements to either close or open the gripper.

The closed vector polygons for the gripper are shown in Figure 2. The mathematical model was created in a manner described in paper [11]. Requiring that the resultants be equal to zero, equations of motion were obtained (system of equations 1).

The system of equations (1) was treated as a vector function y of the independent vector variable Ψ:

$$y = F(\Psi) \tag{2}$$

where:

$$\Psi = (\alpha_1, \alpha_2, \alpha_4, \alpha_6)$$

and its roots are found as functions of the screw angle of rotation φ, being solutions of the set of equations (1).

The dynamic equation of motion can be presented using the principle of virtual work as shown in equation (3), where φ - the rotation angle of the main shaft; I_s - the moment of inertia of the main shaft; I_6, I_7 - the moments of inertia of the gripper elements; r_6, r_7 - the gripper finger lengths; α_2, α_6 - corresponding angles, *Ms* - the motor's driving torque, *N* - the working force.

The motor torque M_S and angle of revolution φ are functions of time *t* and can be found from:

$$e = L\frac{di}{dt} + R \cdot i + Kb\frac{d\varphi}{dt}, \quad i = \frac{M_s}{Kt} \tag{4}$$

where:

i - the current intensity,
L - inductance,
R - resistance,
e - supply voltage,
K_b - voltage constant,
K_t - turning moment constant.

The mechanical and electrical quantities are related to each other as follows.

$$T = \frac{L}{R},\ c = \frac{K_t \cdot K_b}{R},\ \Omega = \frac{e}{K_b},\ i = \frac{M_s}{Kt} \tag{5}$$

where:

T - the time constant of motor,
c - the stiffness of the motor characteristic,
Ω - the angular velocity of the motor shaft at which the moment equals zero.

If the relation between the compressing *N* force and the sample deformation is of the form:

$$\begin{aligned} N &= k_1 u + k_2 u^3 + c\frac{du}{dt}, && \text{for } u>0 \\ N &= 0, && \text{for } u \le 0 \end{aligned} \tag{6}$$

where:

k_1, k_2 - elasticity constants,
c - the averaged coefficient of energy dissipation,
u - the total deformation of the fabric stack, which can be expressed by the following relations:

$$\begin{aligned} u &= g - r_d \\ r_d &= r_7 \sin\alpha_2 + r_6 + r_6 \sin\alpha_6 \ge 0 \end{aligned} \tag{7}$$

$$\frac{du}{dt} = -\frac{dr_d}{dt} = -\frac{d}{dt}\left(r_7 \sin\alpha_2 + r_6 + r_6 \sin\alpha_6\right) \tag{8}$$

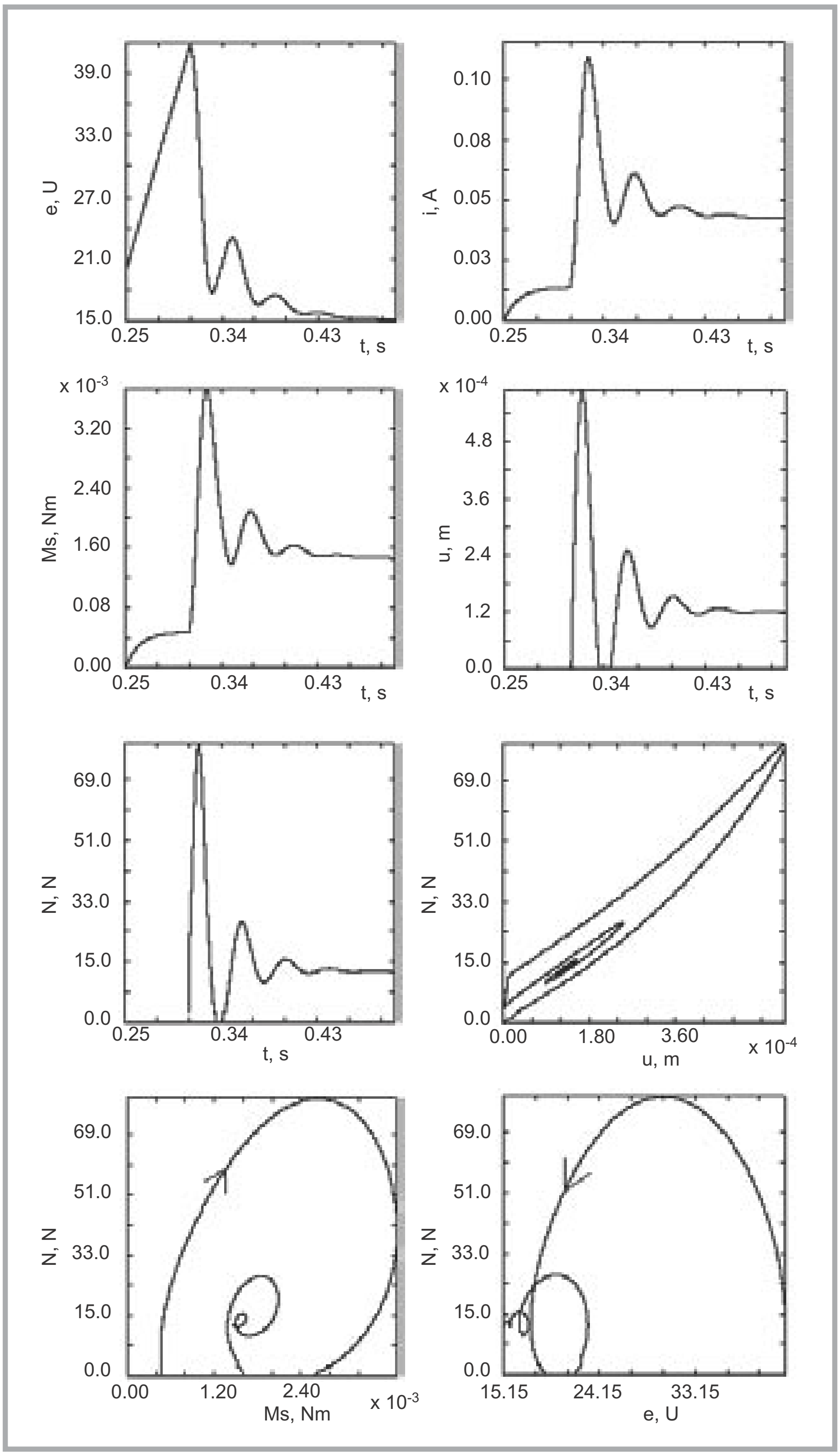

Figure 3. *Time history of the electromotive force e [V], the electric current intensity i [A], the driving torque M_S [Nm], the fabric material deformation u [m], and the force compressing the fabric N [N]; the relationships between N and the following quantities: u, M_S, e.*

The normal force in the sample under consideration is the force which compresses the fabric under the condition of $r_d<g$, where g is the thickness of the fabric stack. If $r_d \ge g$, then the force N=0.

Making use of the formula for the derivative (9), and substituting it into expression (3), the equation (10) is obtained. Denoting angular velocity by the symbol φ_2, one may write equation (10) in the form of a system of first-order equations (11).

A logic feedback element, which controls the gripper work, was introduced in the computer program. Its action follows the following rules: if the compressing force is smaller than the set value ($N<N_{set}$), then the supply voltage will be increased

by a value *de* described by (*e:=e+de*); in contrary, if $N>N_{set}$ then (*e:=e-de*). At the same time, the current intensity cannot be greater than the admissible value.

The value of *de* can be calculated from the following equation:

$$de = \left|\frac{N - N_{set}}{N_{set}}\right| \cdot \left(\frac{N_{set}}{400}\right) \tag{12}$$

Results and Discussion

Using the equations derived above, the Newton-Brent method and the Runge-Kutta method, a computer program simulating the gripper behaviour was written. The calculations were performed for various parameters. Here, only the results obtained for the following parameters are presented:

- the dimensions: (r_1=0.02 m, r_2=0.03 m, r_3=0.18 m, r_4=0.35 m, r_5=0.015 m, r_8=0.04 m, r_9=0.025 m, r_6=0.024 m, r_7=0.029 m, x_0=0.023 m, h_s=0.001 m),
- the mass moments of inertia of the gripper fingers: ($I_7=15\cdot10^{-9}$ kgm^2, $I_6=11\cdot10^{-9}$ kgm^2),
- voltage constant: K_b=0.038 V/(rad·s),
- turning moment constant: K_t=0.033 Nm/A,
- resistance: R=343 Ω,
- inductance: $L=53\cdot10^{-3}$ H,
- the supply voltage: e=100 V, and
- the mass moment of inertia of the motor's rotor: $I_S=5.0\cdot10^{-8}$ kgm^2.

The results of the calculations are shown in Figure 3.

As shown in Figure 3, the electromotive force e was adjusted by the feedback element. The current intensity i and motor torque M_s followed accordingly. At the same time, fabric compression u and compressing force N achieved steady-state values gradually with decaying oscillations.

It is noteworthy that the dependence N=f(M_S) is a multiple-valued function with more then one extreme. For one value of N several values of M_S correspond. The force does not achieve its maximum values for the maximum values of driving torque.

Conclusion

The mathematical model makes it possible to choose gripper parameters at the design stage. The force that the gripper uses on a fabric follows a characteristic accepted by the user.

Acknowledgement

This research was carried on under the guidance of Professor J. Zajączkowski of the Technical University of Łódź. The results were partially presented at the conference of the Faculty of Textile Engineering and Marketing [12].

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Received 28.06.2004   Reviewed 26.10.2004