Electromagnetic Linear Microdrive for Braille Screen: Control and Circuit Test

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***Abstract*—Graphical interfaces based on visual representation and direct manipulation of objects make the adequate use of computers quite difficult for people with reduced sight. A new type of graphical Braille screen is developed. Permanent magnet linear actuator intended for driving a needle in Braille screen has been optimized. The recently developed permanent magnet linear electromagnetic actuator for driving a needle in a Braille screen and the circuit testing method using micro robots are discussed. Also, a planar and spatial motion tactile display with incorporated electromagnetic linear drives into its links is designed. The optimization is carried out with respect to minimal magnet motive force ensuring required minimum electromagnetic force on the mover. The optimization factors include dimensions of the cores and movable parts under additional constraint for overall dimension of the actuator. Finite element analysis, response surface methodology and design of experiments have been employed for the optimization. The static force characteristics and magnetic field distribution is studied when varying the parameters.**

***Index Terms*—linear actuators, permanent magnets, tactile display, micro robots**

I. Introduction

Permanent magnets have been intensively used in the constructions of different actuators in recent years. One of the reasons for their application is the possibility for development of energy efficient actuators. New constructions of permanent magnet actuators are employed for different purposes. One such purpose is the facilitation of perception of images by visually impaired people using the so called Braille screens. Recently, different approaches have been utilized for the actuators used to move Braille dots [1]-[8]. A linear magnetic actuator designed for a portable Braille display application is presented in [1]. Actuators based on piezoelectric linear motors are given in [2], [3]. A phase-change micro actuator is presented in [4] for use in a dynamic Braille display. Similar principle is employed in [5], where actuation mechanism using metal with a low melting point is proposed. In [6], Braille code display device with a polydimethylsiloxane membrane and thermo pneumatic actuator is presented. Braille sheet display is presented in [7] and has been successfully manufactured on a plastic film by integrating a plastic sheet actuator array with a high-quality organic transistor active matrix. A new mechanism of the Braille display unit based on the inverse principle of the tuned mass damper is presented in [8]. Research on development of tactile haptic interface for a Braille display by authors has been studied in the references [9]-[17].

In the present paper, permanent magnet linear actuator for driving a needle (dot) in Braille screen is developed. Methods of circuit testing are discussed. Also, a design concept for planar or 3D motion tactile display driven by electromagnetic linear drives is proposed.

II. Development of a Linear Actuator

A. Development of a Linear Magnetic Actuator

We have developed electromagnetic linear motion actuators for Braille Screen. A CAD model of the linear actuator is shown on Fig. 1.

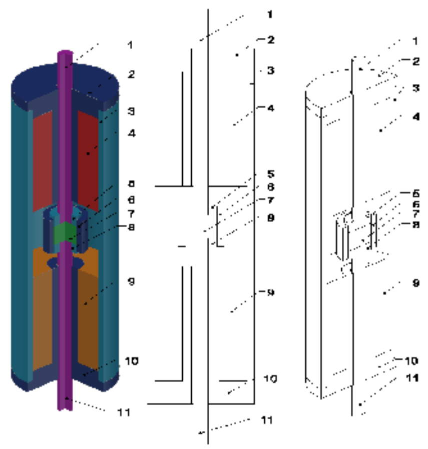

Figure 1. Electromagnetic actuator 3D CAD model.

The real prototype of the linear actuator is depicted on Fig. 2. The moving part is axially magnetized cylindrical permanent magnet with two ferromagnetic discs on both sides. The motion is transferred to the Braille dot using non-magnetic shaft. The actuator consists of: 1 - Needle (shaft); 2 - Upper core; 3 - Outer core; 4 - Upper coil; 5 - Upper ferromagnetic disc; 6 - Non-magnetic bush; 7 - Permanent magnet; 8 - Lower ferromagnetic disc; 9 - Lower coil; 10 - Lower core; 11 – Needle (shaft).

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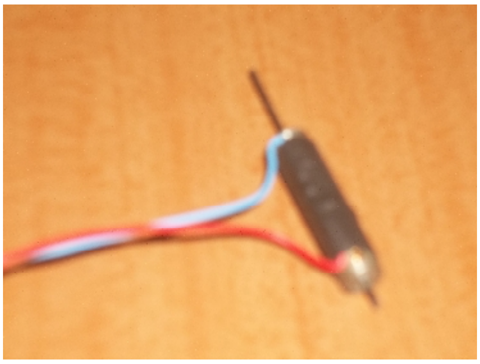


Figure 2. A prototype of electromagnetic actuator.

The two coils are identical and connected in series in such a way that they generate a magnetic flux of opposite directions in the region of the permanent magnet. In this way in accordance with the polarity of the power supply, the permanent magnet will move either up or down. When an upward motion is needed, the upper coil creates flux in the air gap coinciding with the flux of the permanent magnet. Lower coil at the same time generates opposite flux and the permanent magnet will move in an upper direction. When a downward motion is needed, the polarity of the power supply is reversed.

One of the main advanced features of the actuator is its increased energy efficiency, as the need of power supply is only during the switching between the two end positions of the mover. In each end position, the permanent magnet creates holding force, which keeps the mover in this position.

B. *Performance Simulations of the Linear Actuator*

We have performed a finite element modeling in order to study electromagnetic force of the actuator's performance.

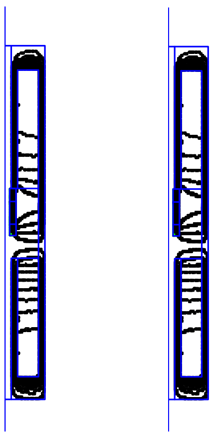


Figure 3. Typical flux lines distribution for three different mover positions.

Axisymmetric model is adopted as the actuator features rotational symmetry. The electromagnetic force acting on the moving permanent magnet is obtained using the weighted stress tensor approach. An example of the flux lines distribution is shown in Fig. 3. In this case, the force on the magnet is in upward direction. More results of this research have been published in papers [9] and [13].

C. *Force Determination of the Linear Actuator*

Linear displacement and force generated by actuators are important to develop tactile force display. Here, we study the static force parameters of the magnetic based linear actuator. The static force characteristics are obtained for different construction parameters of the actuator. The outer diameter of the core is 7 mm. The air gap between the upper and lower core, and the length of the permanent magnet and the coil heights has been varied. Fig. 4 and Fig. 5 depict the force-stroke characteristics given for different values of the permanent magnet height h_m, coil height h_w, magneto motive force I_w and apparent current density in the coils J. Supply of the coils is denoted with c_1 and c_2. The diameter of the mover is depicted with δ. The coefficients $c_1=-1$, $c_2=1$ represent the supply for motion up and the pair $c_1=1$ and $c_2=-1$ – motion down. When $c_1=0$ and $c_2=0$, there is no current in the coil, i.e. this is the force due only to the permanent magnet. More extensive research on the determination of the static forces is conducted and published in the article [14] and [17].

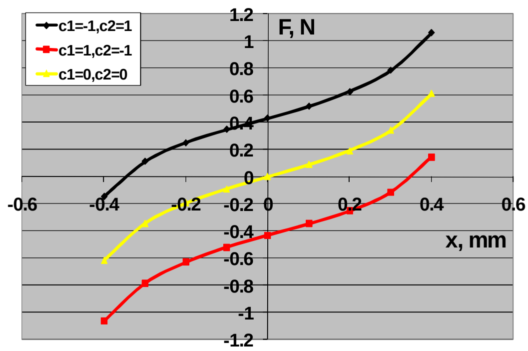


Figure 4. Force-stroke characteristics for $h_m=2$ (mm), $\delta=3$(mm), $h_w=5$ (mm), $I_w=180$ (A), $J=20$(A/mm^2).

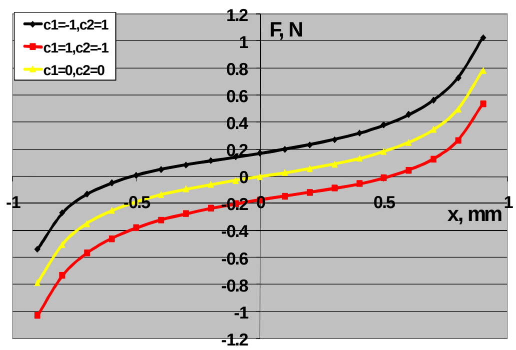


Figure 5. Force-stroke characteristics for $h_m=2$ (mm), $\delta=5$ (mm), $h_w=10$ (mm), $I_w=180$ (A), $J=10$ (A/mm^2).

On the basis of our experiments, we can conclude that the major parts of the force characteristics are suitable for Braille screen application. The holding force for the case of h_m=2mm, δ=5mm was experimentally verified.

D. *Linear Actuator Optimization*

The objective function is minimal magnet motive force of the coils. The optimization parameters are dimensions of the permanent magnet, ferromagnetic discs and the cores. As constraints, minimal electromagnetic force acting on the mover, minimal starting force and overall outer diameter of the actuator have been set. The optimization is carried out using sequential quadratic programming. To optimize the linear actuator performance the following parameters ware considered

- N_I —ampere-turns—minimizing energy consumption with satisfied force requirements;
- F_h —holding force—mover (shaft) in upper position, no current in the coils;
- F_s—starting force—mover (shaft) in upper or lower position and energized coils;
- J — coils current density;
- h_w, h_m, h_d—geometric dimensions.

Minimization of magneto-motive force N_I is a direct consequence of the requirement for minimum energy consumption. The lower bounds for the dimensions are imposed by the manufacturing limits and the upper bound for the current density is determined by the thermal balance of the actuator.

The radial dimensions of the construction are directly dependent on the outer diameter of the core – D whose fixed value was discussed earlier. The influence of those parameters on the behavior of the construction have been studied in previous work [15], [16] that make clear that there is no need radial dimensions to be included in the set of optimization parameters Fig. 6.

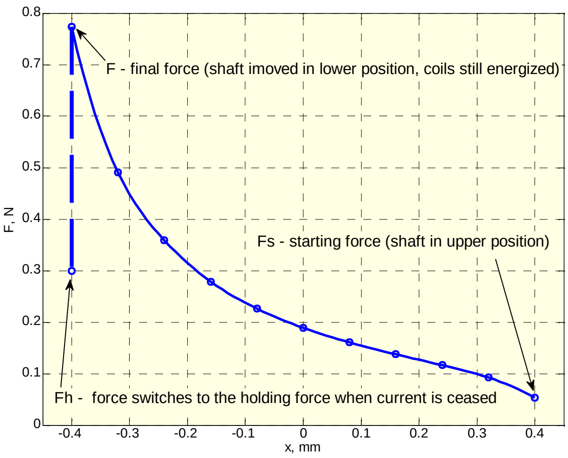


Figure 6. Force-stroke characteristic of the optimal actuator. Coils are energized. The shaft is displaced from final upper to final lower position.

The force constraints for F_s *and* F_h are active which can be expected when minimum energy consumption is required. The active constraint for h_w is also expected because longer upper and lower cores size, which respectively means longer coils, will increase the leakage coil flux and corrupt the coil efficiency.

In (Fig. 7 and Fig. 8), the magnetic field of the optimal actuator is plotted for two cases. The first one is magnetic field of the optimal actuator with shaft in upper position and coils energized to create downward force (Fig. 7). In the second case, coils are not energized (Fig. 8). More results of this research have been provided in papers [16] and [17].

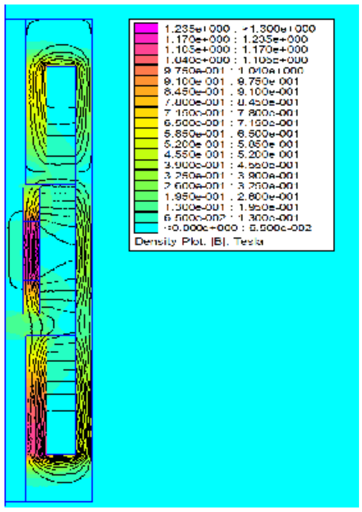


Figure 7. Magnetic field of the optimal actuator with shaft in upper position and energized coils.

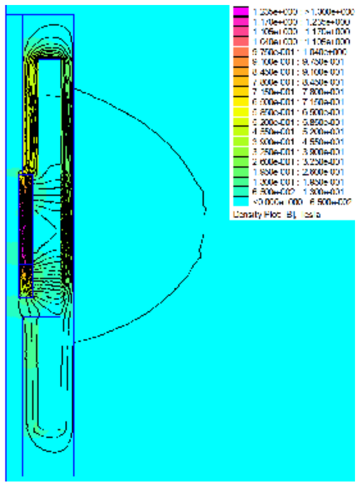


Figure 8. Magnetic field of the optimal actuator with no current in the coils.

III. Development of a Linear Actuator

A tactile matrix for Braille screen is designed (Fig. 9) and developed (Fig. 10). The developed electromagnetic linear motion micro actuators (Fig. 2) discussed into the previous chapter is put into the matrix (Fig. 10).

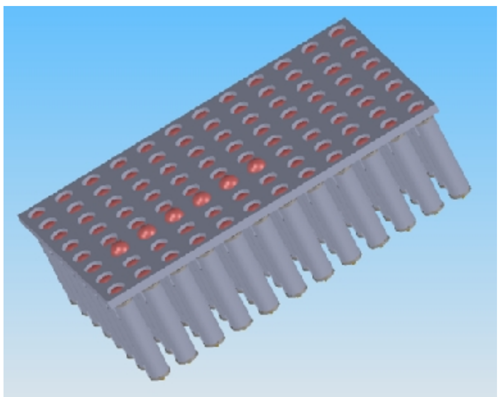


Figure 9. A 3D CAD model of the Braille screen.

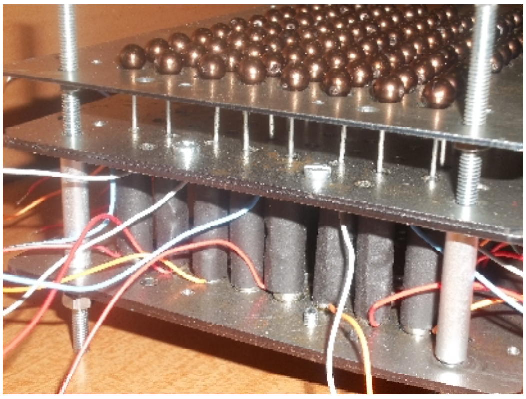


Figure 10. A prototype of a Braille screen with needles (dots) driven by linear actuators.

For better resolution of the graphical images the Braille screen must be larger, for example 96x64 linear micro drives (pixels). It is more than 6000 elements in human hand size with 4 coil connectors for each. In this case we need a strong electro-mechanical test of the entire circuit. We plan to use micro robots for positioning and testing, [15]-[19]. We are developing a smart micro robot with 3 DoF (Degree of freedom) and piezo effectors. Its structural scheme is shown on (Fig. 11). This micro manipulator consists of 1-base; 2, 3, 11-mobile links; 4, 5, 7-elastic connections; 6, 8, 12-piezo actuators; 9, 10-hard connections; 13-sensing element.

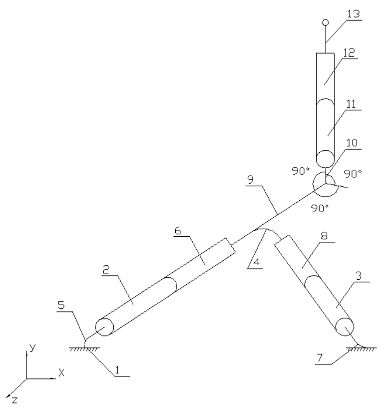
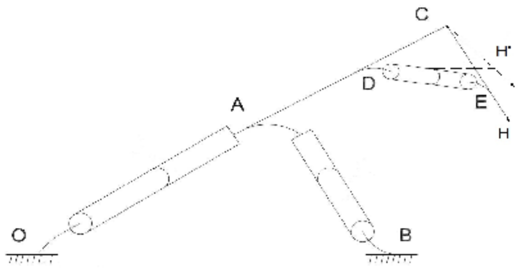


Figure 11. Micro manipulator with 3 DoF and incorporated electromagnetic actuators into its links.

A. Desing and Modeling of a Tactile Display

We have been developing tactile force displays based on electromagnetic linear motion actuators. Generally, planar and spatial motion tactile devices (Fig. 12 and Fig. 13) are being designed and modeled. In this research the designed tactile mechanisms will be used for development of Braille screen. More in particular, we are focused on the design of mechanisms with close kinematic chain (CKC) driven by electromagnetic actuators. The main advantages of this type of mechanisms are: considerable decrease in the weight of mechanical systems; reduced inertial forces–increased accuracy; reduced backlashes when links are connected by revolute joints. Also, there are some disadvantages typical for them, such as compensation of the hysteresis. In addition, mechanisms with CKC and incorporated actuators into their links could be used for precise linear motion mechatronics systems and robots. Geometrical syntheses of 3 DoF planar mechanisms are discussed below.



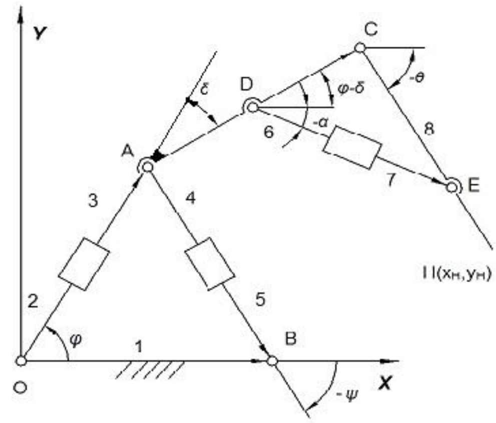


Figure 12. Structural scheme of 3 DoF mechanism with electromagnetic actuators.

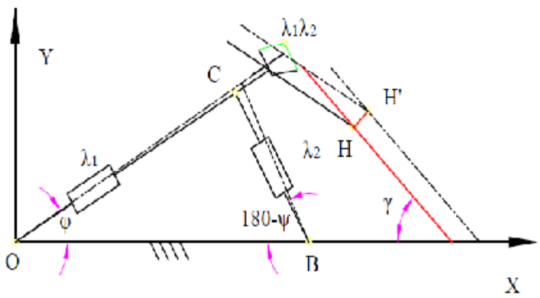


Figure 13. Structural scheme of 2 DoF mechanism with electromagnetic actuators.

In the structural schemes (Fig. 12 and Fig. 13) electromagnetic driven links are illustrated as prismatic pairs. λ_1 and λ_2 represent linear displacement of the device's end-effector when actuators are switched on. The output link of the manipulator or tactile device can position point H and orientate the link in the plane of motion. Therefore, these types of tactile devices are able to represent and to resolve the force into components. Fig. 13 shows a case when the manipulator's end-effector performs rectilinear trajectory motion. Also, the manipulator's work area is shown on (Fig.13). With given coordinates of point *H (x,y)* and *H′(x,y)* or line H-

H′ of the mechanism's output link, the problem will be solved if the following are given:

- Linear equation;
- Angle of the slope of the straight line;
- Linear equation passing through 2 points.

We assume that the slope of line (κ) i.e. necessary linear trajectory) is given:

$$k = tg\gamma \tag{1}$$

where γ is a given slope of the line

$$K_{HH'} = \frac{y_H - y_H^{'}}{x_H - x_H^{'}} \tag{2}$$

$$x_c = x_H^{'} - l * \cos\theta, \quad y_C = y_H^{'} + l * \sin\theta \tag{3}$$

$$x_A = x_C - l_2 \cos(\phi - \delta), \quad y_A = y_C - l_2 \sin(\phi - \delta) \tag{4}$$

In order to control the designed tactile devices with CKC mechanisms or micro motion manipulator the Forward and Inverse kinematics are required. The dynamics of the tactile devices could be derived easily from the equations from (1) to (3). After that the transfer function will be defined. We define the relations between the driving force of the actuators and the displacement of the construction and the end-effector of manipulators (Fig. 13). Also, the stress and stiffness of the constructions due to actuators forces are found.

IV. CONCLUSIONS

Braille screen interface causing force sensation on the user's hand has been developed. Electromagnetic linear motion micro actuators are developed and manufactured to drive the tactile Braille screen. The permanent magnet linear actuator is intended to drive a needle in Braille screen. The mover of the actuator consists of a permanent magnet and ferromagnetic discs. Moreover, we have studied and optimized this magnetic based linear actuator. The optimization is carried out with respect to minimal magnet motive force ensuring required minimum electromagnetic force on the mover. The optimization factors are dimensions of the cores and mover parts under additional constraint for overall dimension of the actuator. In addition, to achieve better dynamics and construction of the linear actuator finite element method analysis has been done. Many experimental tests have been done on electromagnetic linear actuator in order to control Braille screen. The obtained results of our research show that actuator's static force characteristics are suitable for Braille screen application. We have been working on the control of the developed Braille screen.

To achieve better contact force representation on the user's hands mechanisms with closed kinematic chain and actuators incorporated into their links have been designed. We are developing a tactile force display based on these mechanisms.

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