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Development of a Braille Tactile Device Driven by Linear Magnet Actuators

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Abstract*— A Braille display is an electro-mechanical device representing braille characters, usually by means of round-tipped pins raised through holes in a flat surface. We develop a tactile Braille display device which is able to represent graphical information like simple pictures or computer icons on the users' hand. Generally, the developed mechanical construction of the tactile hand device consists of a frame with flat surface upper plate matrix type with 96 holes and 96 pins, respectively. The pins are driven by linear motion electromagnetic actuators. The pins perform up and down motion with less than 4mm stroke. The main focus of the paper is dedicated on the development and optimization of the linear motion magnetic actuators as well as the design concept of the Braille tactile device. Permanent magnet actuators driven pins in the Braille display matrix are developed and optimized. Moreover, the static force properties and magnetic field distribution of the linear motion actuators are studied in different values of their parameters. The optimization factors include dimensions of the cores and movable parts under additional constraint for overall dimension of the actuator. In order to optimize both construction and performance of the magnet actuators, finite element analysis and experiments have been done. Also, it is proposed a design concept for development of control interface for the Braille tactile device. In addition, mechanisms for testing of each pin performance or linear actuators of braille matrix are designed. These mechanisms are intended to hold sensors. Also, applications of linear magnetic actuators in spatial tactile devices as well as in micro motion robotics are discussed.

Index Terms—**Tactile hand display, linear actuators.**

I. INTRODUCTION

Braille is a tactile writing system used by the blind and the visually impaired people. It is traditionally written with embossed paper. Braille-users can read computer screens and other electronic supports thanks to refreshable braille displays [1-3]. A refreshable braille display or braille terminal is an electro-mechanical device for displaying braille characters, usually by means of round-tipped pins raised through holes in a flat surface [2,3].Within the European Union the problem with the access of blind people to computer resources is quite pressing [4,5]. Studies on European and world scale are carried out in many directions:

- A basic direction is the attempt for social integration of the visually impaired. Significant efforts are made in Germany. Since 2000 year visually impaired students are taught in Informatics, Computer sciences and Computer systems. After 2007 students of other technical courses are also involved and even education in Architecture is planned;
- Development of Braille terminals, printers and adaptation to computer systems. Braille terminals and printers are produced by leading European and world companies in various sizes. The impediment here is the fact that there is no unified system for representation of graphical and mathematical elements. Braille terminals, however, are not widely used due to their high price and they are suitable only where there are mainly text interfaces – philology, judicial sciences, economics;
- Computer – human interface. Since the communication man-computer was quite simple (mainly based on text instructions) solution of the problem was sought on the basis of voice synthesis or other forms of feedback [1]. These techniques have been developed before the graphical interfaces but they provide possibilities to form simple feedback to the user as voice commands. The existence of graphical interfaces and their establishment as standard made the interaction of visually impaired with computers very difficult [7], [14]-[16];
- Development of haptic interfaces based on electrically addressable and deforming polymer layer. Practically, the efforts are aimed at manufacturing of a haptic dynamic input-output device allowing visually impaired people to obtain video information in other form. Technologically, the haptic devices provide great possibilities but the production of such terminal devices appears to be quite expensive at present. There are many problems with the 2D haptic representation of more complex geometrics models like images and space maps [2]. Generally, the haptic devices can apply force vector only at a single point of human body [9]. The introduction of the graphical interfaces, however, brought serious problems for the visually impaired people [14]. The graphical interfaces based on the visual representation and direct manipulation with objects turned out to be a big obstacle for the unsighted people to effectively use computers. After 1990 the jobs of many visually impaired people were threatened with migration from textual to graphical interfaces in offices and companies [7], [15], [16]. Actually, the investment in efforts the results of which will provide effective access to computers for people with reduced sight appears to be quite pertinent. The present paper provides design concept for development of a Braille tactile display device. Our aim is to develop tactile display device which is

able to present graphical information like simple pictures on users' hand. In the next section research on design, optimization and development of magnetic based linear actuator have been done. In section III a tactile display has been made. After that in IV control human-computer interface of braille tactile device is proposed. Finally, mechanisms for planar and spatial motion tactile devices driven by linear magnetic actuators are discussed. Also, the designed mechanisms are intended to hold sensors in order to test each pin or linear actuator of our Braille matrix.

II. DEVELOPMENT OF A MAGNET ACTUATOR

In recent years permanent magnets have been intensively used in the constructions of different actuators. 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. 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 poly dimethy lsiloxane 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].

A. *Design of Magnet Actuators*

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

The real prototype of the linear motion electromagnetic 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 stroke of the actuator is less than 4 (mm). 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.

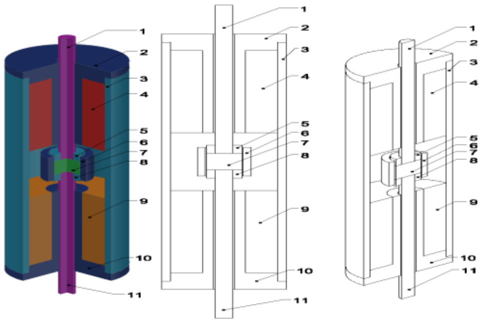


Fig 1. An electromagnetic actuator - 3D CAD model.

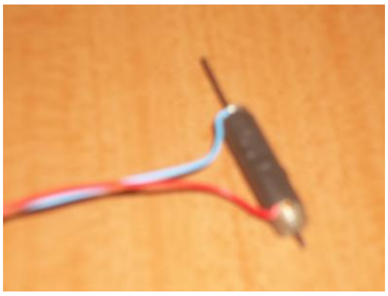


Fig 2. A prototype of electromagnetic actuator.

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. *Magnet Flux Modeling of the Linear Actuators*

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

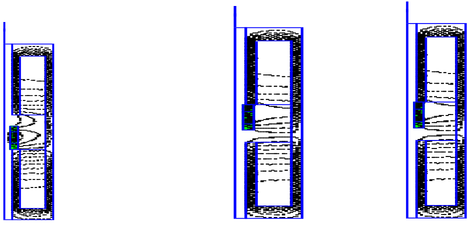


Fig 3. Typical flux lines distribution for three different mover positions.

An example of the flux lines distribution is shown in Fig. 3. In this case, the force on the magnet is in upward direction. From the three types of electromagnets studied, the third one features much higher forces on the mover and that is why this is the type that should be studied in more details as suitable for Braille screen application. From the four variants of this construction, the one with nonmagnetic needle and ferromagnetic poles gives the highest electromagnetic force.

C. *Force Deformation and Simulations*

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 actuators. 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. Figures 4, 5, 6, 7 and 8 depict the force-stroke characteristics given for different values of the permanent magnet height (h_m), coil height (h_w) magneto-motive force Iw 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].

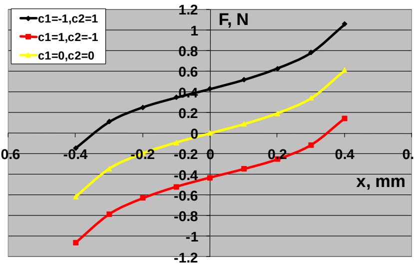


Fig 4. Force-stroke characteristics for h_m=2(mm),
δ=(3mm), h_w=5(mm), I_w=180 (mA), J=20 (A/mm^2)

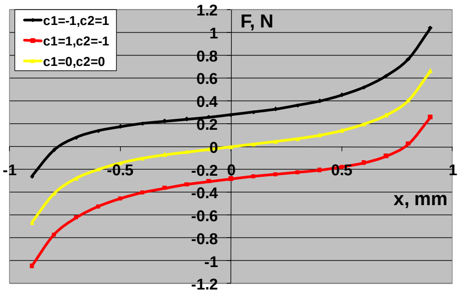


Figure 5. Force-stroke characteristics for h_m=2(mm),
δ=4(mm), h_w=5(mm), I_w=180 (mA), J=20 (A/mm^2).

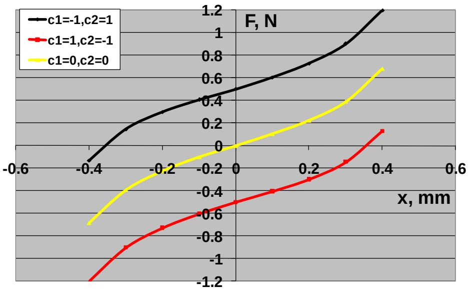


Fig 6. Force-stroke characteristics for h_m=3(mm), δ=4(mm), h_w=5(mm), I_w=180 (mA), J=20 (A/mm^2).

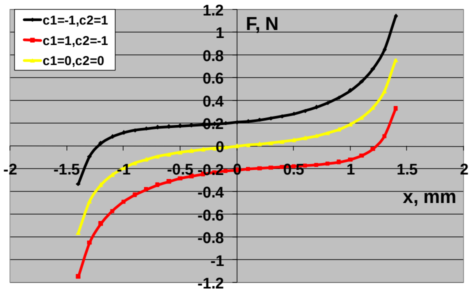


Fig 7. Force-stroke characteristics for h_m=3(mm), δ=6 (mm), h_w=5(mm), Iw=180 (mA), J=20(A/mm^2)

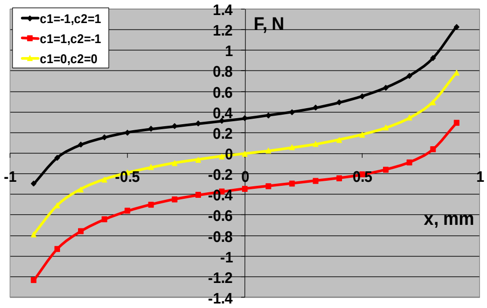
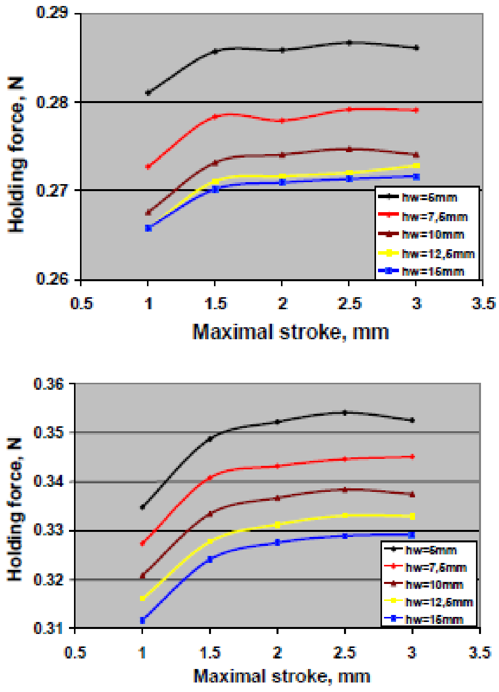


Fig 8. Force-stroke characteristics for h_m=4(mm), δ=6(mm), h_w=5(mm), I_w=180 (mA), J=20(A/mm^2).

On the basis of our experiments we can conclude that the major parts of the force characteristics are suitable for Braille screen application. Experiments study holding force for different values of δ (from 3 (mm) to 6 (mm)) and h_m (from 2(mm) to 4 (mm)) are done (Fig. 4-8). The obtained relationships in Figures 4- 8 show that the permanent magnet height h_m and the diameter of the mover δ have significant influence on the initial force, especially at greater maximal strokes – up to 50% increase. This is due to the increased leakage flux. Thus further increasing of the coil height is practically not recommended. Having in mind that greater coil height leads to lower holding force an optimal value could be sought. In Fig. 9 and 10, the relationship between the holding force at upper position and the maximal stroke is shown for different values of the coil height h_w and outer *diameter d*.



a)

b)

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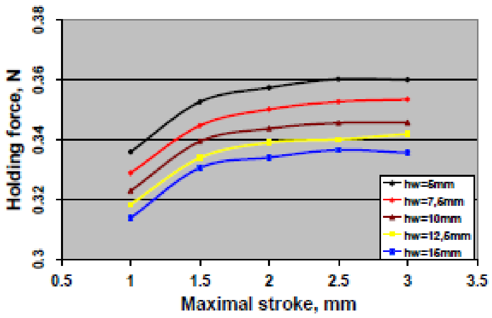

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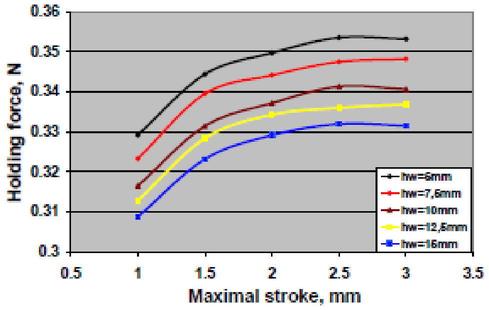
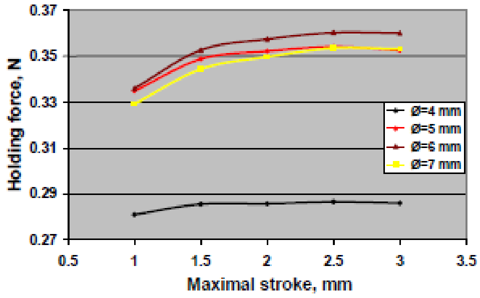
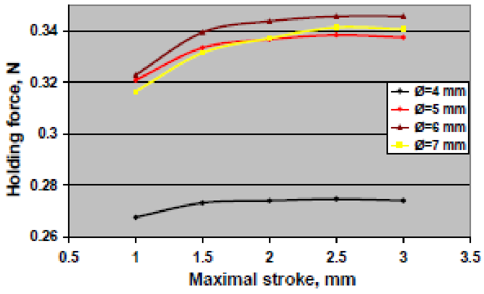


d)

Fig 9. Influence of the holding force on the maximal stroke for different coil heights: a) d=4(mm); b) d=5 (mm); c) d=6 (mm); d) d=7 (mm).

a)





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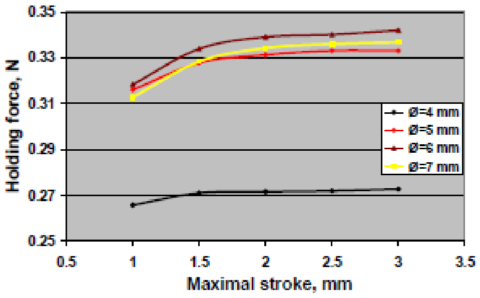

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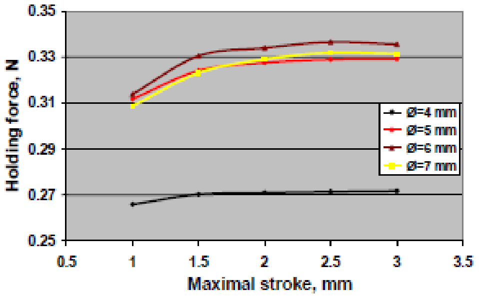

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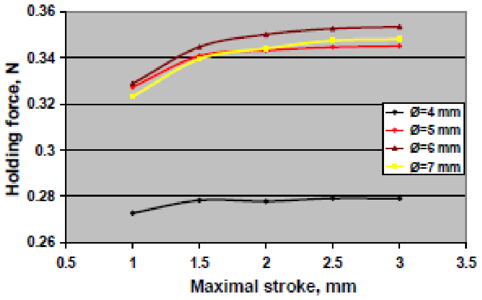

Fig 10. Infiuance of the holding force on the maximal stroke for different outer diameter Ø at coil height: a) h_w=5(mm); b) h_w=7.5 (mm); c) h_w=10 (mm); d) h_w=12.5 (mm); e) h_w=15 (mm).

The obtained results show that increasing the coil height leads to lower holding force, while dependence on the outer diameter features a maximum. This could be seen more clearly in Fig. 11, where the latter is shown for one value of the maximal stroke 1 (mm).

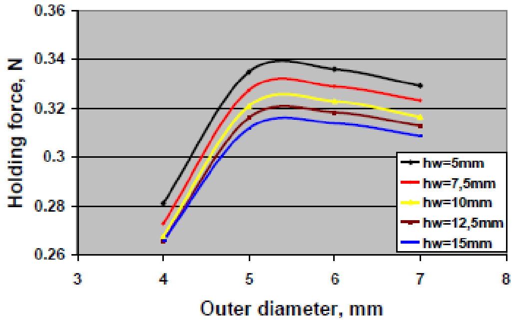

Fig 11. Dependence of the holding force on the outer diameter for *1 (mm)* maximal stroke and different coil heights h_w

Another important parameter, as mentioned above, is the initial force at starting position of the mover (e.g., lower position for movement upward). Here, in addition to other factors, also the current density in the coils is varied.

D. 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 are considered

- *NI* — 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.

The canonic form of the optimization problem is:

$$min\{NI\} \tag{1}$$

$$\left| \begin{array}{c} 5 \le hw \\ 0.5 \le hm \\ 0.3 \le hd \\ 0 \le J \le 25\ A/mm2 \\ Fh \ge 0.3N \\ Fs \ge 0.05N \end{array} \right. \tag{2}$$

Minimization of magneto-motive force *NI* 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.

The optimization is carried out by sequential quadratic programming. The optimization results are as follows:

$$NI_{out} = 79.28\ \ A \tag{3}$$

$$h_{w,opt} = 5\ mm \tag{4}$$

$$h_{m,\ opt} = 2.51\ mm \tag{5}$$

$$Hd_{opt} = 1.44\ mm \tag{6}$$

$$J_{opt} = 19.8\ A \tag{7}$$

The optimal parameters were set as input values to the FEM model. The force-stroke characteristics of the optimal actuator are shown in Fig. 12 and 13. 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. The magnetic field of the optimal actuator is plotted for two cases in the Fig. 14 and 15. The first one is magnetic field of the optimal actuator with shaft in upper position and coils energized to create downward force (Fig. 14). In the second case, coils are not energized (Fig. 15).

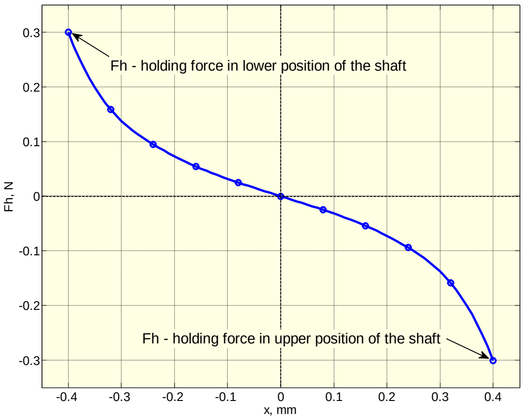

Fig 12: Force-stroke characteristic of the optimal actuator. The force is created by the permanent magnet only (no current in the coils).

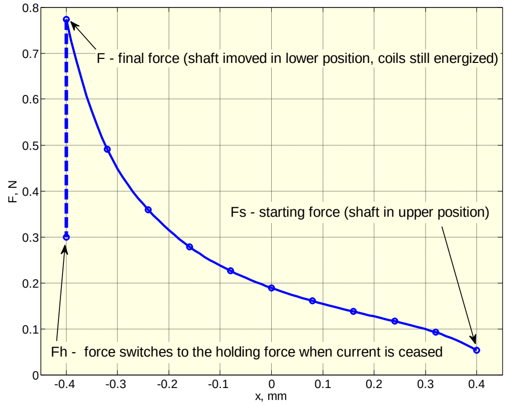

Fig 13. Force-stroke characteristic of the optimal actuator. Coils are energized. The shaft is displaced from final upper to final lower position.

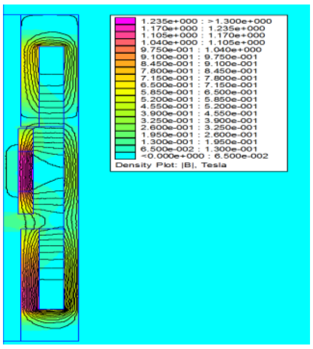

Fig 14. Magnetic field of the optimal actuator with shaft in upper position and energized coils.

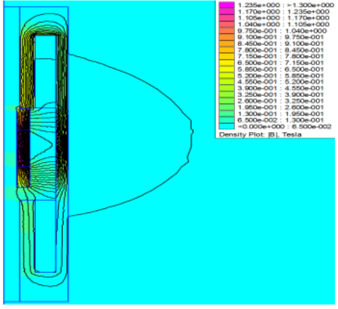

Fig 15. Magnetic field of the optimal actuator with no current in the coils.

III. DEVELOPMENT OF A BRAILLE DISPLAY DEVICE

A tactile matrix for Braille screen is designed (Fig. 16) and developed (Fig. 17). The developed electromagnetic linear motion micro actuators discussed into the previous chapter were put into the matrix. Also, addition information is provided in the following reference [10-12].

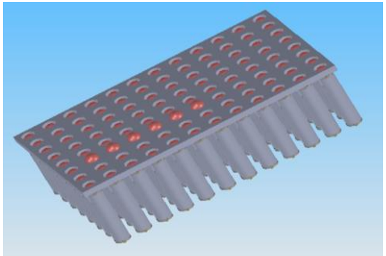

Fig 16. A 3D CAD model of the Braille screen.

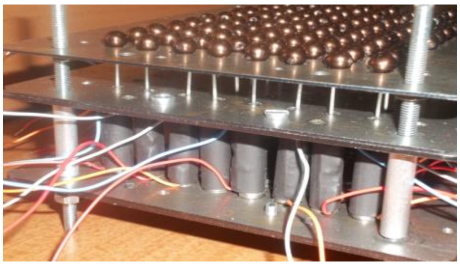

Fig 17. A prototype of a Braille screen with needles (dots) driven by linear actuators.

Generally, the developed mechanical construction of the tactile hand device consists of a frame with flat surface upper plate matrix type with 96 holes and 96 pins, respectively. The holes and pins are located in a matrix with 8 rows and 12 columns (Fig. 17). The pins perform up and down motion with less than 4mm stroke. For better resolution of the graphical images the Braille screen must be larger, for example 96x64 linear micro drives (pixels) [11]-[13]. 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 [17-19].

IV. CONTROL

A. Computer-Human Interface for Visually Impaired People

Most of the interfaces developed for visually impaired people are designed for those who had not lost their sight totally. Many interfaces use various other types of feedback like haptic and/or tactile feedback but these interfaces are usually some kind of supplement to the visual communication [1-7]. There is a set of certain movements of the hand and fingers which are intuitively used by people to perceive different physical properties of the objects by touching. These movements can be grouped to form exploration procedures:

- Movement aside;
- Pressure;
- Static contact;
- Encircle and follow object contour.

The people with reduced or no sight use these model in a similar way. An important component of the ability to create cognitive models for objects in the physical world is closely related to the sense of touching. This is the only sense allowing simultaneous input/output interaction in both directions [15]-[16]. The usual interfaces use only one direction when interacting with the user while the tactile-voice interface can well utilize the two-way communication, thus increasing the amount of information exchanged between the interface and the user.

B. Voice Interface

So far as the modeling of human speech is concerned, it could be formed by separate components combined in a common system [20]. For this purpose, it is necessary to model a vocal tract which will be the basis for the design of the voice synthesizer, [21]. Formal modeling could be realized through a model of the oral cavity from the larynx to the lips. To realize comparatively adequate model certain number of parameter must be introduced to form articulate vector and define the personal characteristics of each individual. The model of human vocal tract basically consists of three components:

- Oral cavity;
- Glottal functional apparatus;
- Acoustic impedance at the lips.

Generally, the oral cavity is modeled as an acoustic tube with slowly changing (in time and space) cross-section where the acoustic waves propagate unidirectional. Under these conditions, the following equations are suggested to calculate the pressure and volume velocity [15]-[16]. The operation system of the autonomous device should guarantee its performance rate which implies modification of some of its kernel functions. According to the discussion on the job of the autonomous device, its general structure should be built in modules using as much as possible standard interfaces for communication with computer systems. The basic scheme of the interface and its place in the frame of LAN working computer system is shown on the Fig. 18.

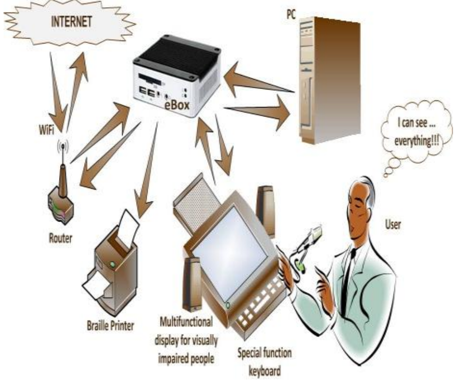

Fig 18. Scheme of the whole system

The main computer is eBox-3310AMSJK, because of the functionality, small size and universality. Here it works with Windows Embedded CE and it is easy to make the other hardware and software.

V. DESIGN OF BRAILLE SCREEN TEST DEVICE

We have been developing test device which is able to measure both *force* and *displacement* of the electromagnetic linear actuators of Braille matrix (Fig. 17). The proposed test device is intended to held sensors measuring forces and displacement of each pin of the Braille screen matrix. Generally, planar and spatial motion test devices are being designed and modeled. More in particular, we are focused on the design of mechanisms with close kinematic chain (CKC) driven by linear actuators (Fig. 19).

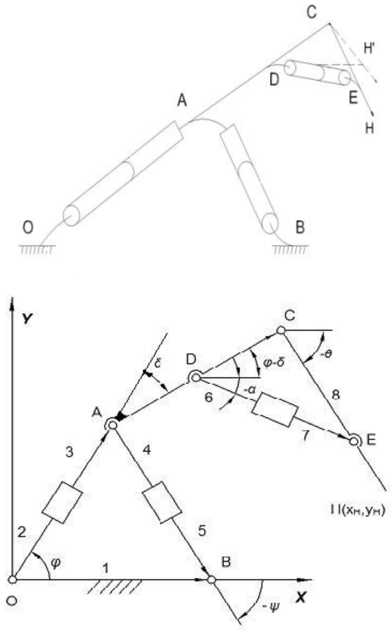

Fig 19. Structural scheme of 3D oF mechanism with linear actuators.

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 [17-19]. 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 [17, 18]. Geometrical syntheses of 3 DoF planar mechanisms are discussed below. We are developing a smart micro manipulator with 3 DoF (Degree of freedom) and piezo effectors. Its structural scheme is shown on Figure 19. 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. In the structural schemes of Figure 16 linear 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 test device can position point *H* and orientate the link in the plane of motion. Therefore, these types of devices are able to represent and to resolve the force into components. In a case when the manipulator's end-effector performs rectilinear trajectory motion. 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/known:

- 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:

$$k = tg\gamma \tag{8}$$

Where γ is a given slope of the line

$$K_{HH'} = \frac{y_H - y_H'}{x_H - x_H'} \tag{9}$$

$$x_c = x_H' - l * \cos\theta, \quad y_C = y_H' + l * \sin\theta \tag{10}$$

$$x_A = x_C - l_2\cos(\ \phi - \delta), \quad y_A = y_C - l_2\sin(\phi\ - \delta) \tag{11}$$

In order to control the designed test device with CKC mechanisms or micro motion manipulator the Forward and Inverse kinematics are required. The dynamics of the test device could be derived easily from the equations from (9) to (11). 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. 19). Also, the stress and stiffness of the constructions due to actuators forces are found. In addition these mechanisms (Fig. 19) could be used for development of a planar or spatial motion tactile force displays.

VI. CONCLUSION

The Braille screen interface causing force sensation on the user's hand has been developed. It is able to represent graphical information such as icons and pictures from computer screen to users' hand. Electromagnetic linear motion actuators are developed and manufactured to drive the tactile Braille screen. The permanent magnet linear actuators are intended to drive pins 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. The obtained relationships in Figures 4 - 8 show that the permanent magnet height h_m and the diameter of the mover δ have significant influence on the initial force, especially at greater maximal strokes. 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. Current density of *15*

(A/mm^2) could ensure enough initial force at lower starting position of the mover. We have been working on the control of the developed Braille screen. In addition, in order to test contact force representation of each pin of the tactile matrix sensor, held mechanisms are designed. These mechanisms have closed kinematic chains and actuators incorporated into their links. Also, these mechanisms could be used for development of a planar or spatial motion tactile force displays.

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