Mechanism Design for Haptic Handwriting Assistance Device

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Abstract One of the applications of haptic technology is in education and training. Handwriting for first year-elementary students has been included in the curriculum for some years in Turkey as the first and only writing skill to be taught. Providing these students with a haptic assistance device during the handwriting learning process is the global aim of this work. Among the other components of the design such as electronics, controls and communication, mechanism design is a critical component to be considered for optimization of the device at different levels. This paper aims to address a solution to meet the design criteria through ergonomic design for user along with optimized force exertion capabilities.

Keywords Haptics · Planar 5R mechanism · Mechanism design · Assistive device

1 Introduction

Haptics literally means sense of touch and haptics technology aims at transmitting this sense from one location to another location. Haptics technology finds application in assisting the blind [1], education [2], training [3], computer-aided design [4], medical field [5], entertainment [6], automotive industry [7], mobile phones [8] and even art [9]. Depending on the application specifications, a variety of haptic devices can be produced. If the application aims at stimulating cutaneous sensory system, in which the receptors under the skin are targeted, a group of devices called tactile haptic/cutaneous haptic interfaces are considered. In this case, the stimulated sensation is temperature, texture, slip, vibration, force or pain.

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Kinesthesia is the sense that detects bodily position, weight, or movement of the muscles, tendons, and joints. The receptors of this sensation are usually located in the joints and muscles of the human body. Therefore, if a haptic interface is developed to stimulate kinesthesia senses, it aims to stimulate sense of location/configuration, motion, force or compliance. In training or education type of applications, motion and rendering of slave side induced forces plays a vital role. Hence, most of the education or training type of applications calls for kinesthetic haptic devices. Haptic devices coupled with other human-computer interfaces, such as three-dimensional (3D) virtual reality (VR) visualization systems, are referred to as haptic systems. Many researchers have developed education or training purpose haptic systems based on the existing general purpose haptic devices [10–12].

One commercially available example of these type haptic systems is the dentistry trainer by Moog [13]. Main difference of this system from the previously mentioned ones is that a new haptic interface is specifically developed for the system. Workspace, motion and force rendering capabilities are selected according to the application and the device is constructed accordingly.

Application considered in this study is assistive system for handwriting education/rehabilitation. The need in education arises from recent changes in the education system of Turkey. Since couple of years, first graders in elementary school start to learn to write by handwriting. In a classroom of 30 or more students, it becomes impossible for the teacher to work with every student one on one. Hence, a possible teleoperated or automated system to assist the student at early stages can fill this gap in education. In the later stages, the same system can be used as a source of evaluation of the learnt handwriting skills.

In rehabilitation there are two potential needs at different levels. In a more severe case scenario, it can be used for post-stroke patients to re-gain motor neurons for performing finer motor skills through BCI-based initiation of the task. This requires a joint research with neuroscientists in order to correctly locate the neurons to work with. For course motor neuron training, various studies exist in the literature [14]. Another case for rehabilitation is the motor skill rehabilitation of post-injury patients.

Since the application is specifically focused on writing skills, modifying existing haptic devices is not the choice since they are manufactured usually for 3D motion. There have been studies on developing handwriting assistance systems with such general-purpose haptic interfaces [15]. As a result of this, a planar haptic device for handwriting assistance is designed and presented in this paper. Next section describes design criteria followed by the description of the initial design and optimization of the design with respect to force exertion capability throughout the workspace.

2 The Design Criteria

grasp. This type of grasp is used for handwriting and holding tools for precise operations. The amount of forces that a person can exert in this type of a grasp is limited to 1 N in average, hence the devices built for this type of grasp and precise operations (Phantom Omni$^{®}$ [16]) are developed around this range of force exertion. The maximum amount of force to be reflected to the user is selected to be at 1 N throughout the workspace of the device. Although an equal amount of maximum force exertion throughout the workspace cannot be achieved (unless the manipulator is not a PP type of mechanism), an optimization criteria is described as to have equal force ranges throughout the workspace.

Another design criterion is set for the workspace dimensions to cover a writing range on an A4 (297 mm × 210 mm) paper. The location of the workspace is to be optimized for the ergonomics of the user being right-handed. The performance criterion in this optimization is to enable a visual feedback of the written letters at all times.

Writing requires the positioning of the tip of the pen on a planar surface, therefore the task space is two dimensional and it is required to design a two degrees-of-freedom (dof) planar mechanism. For the structure of the device, a parallel mechanism is preferred over a serial one due to its higher precision capability [17]. We confined ourselves with single loop planar mechanisms with revolute (R) and prismatic (P) joints only. The following considerations are taken into account for the selection of the kinematic structure of the mechanism: (1) the actuated joints should be grounded, (2) If exists, prismatic joints should be actuated, (3) the topological structure of the mechanism should be symmetric. Of all possible alternatives only $\underline{\mathrm{R}}\mathrm{RRR}\underline{\mathrm{R}}$ (5R) and $\underline{\mathrm{P}}\mathrm{RRR}\underline{\mathrm{P}}$ comply with these conditions. For the planar writing application 5R mechanism is chosen due to compactness and force transmission characteristics.

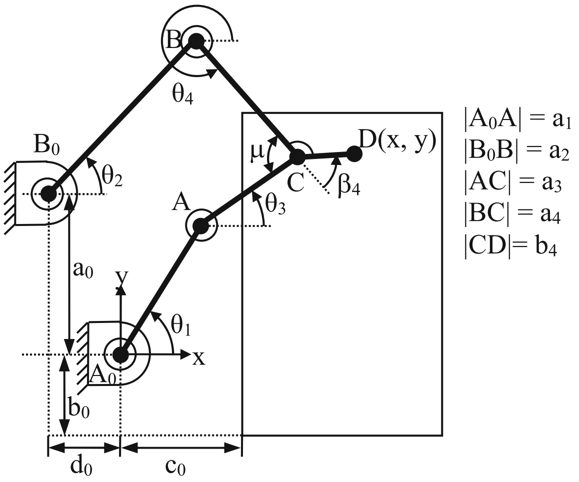
3 Mechanism Analysis and Design Optimization

The mechanism structure to be designed and an A4 paper are illustrated in Fig. 1.

3.1 Static Force Analysis

The direct and inverse kinematic analysis formulation is performed, however for brevity, we do not present the kinematic formulation here. In this application, inertial forces are not comparable with the external forces (due to selecting high strength to weight ratio link structures), therefore dynamic effects are ignored in design stage. We shall use virtual work principle in order to obtain relation between the actuator torques, $\mathbf{T}_1$ and $\mathbf{T}_2$, and external force, $\mathbf{F}_{04} = F_{04} \measuredangle \phi$. The total virtual work done on the system:

Fig. 1 5R mechanism



$$F_{04}\mathrm{c}\phi\delta x + F_{04}\mathrm{s}\phi\delta y + T_1\delta\theta_1 + T_2\delta\theta_2 = 0 \tag{1}$$

The velocity level kinematic analysis results in

$$\begin{aligned}
\delta x &= \frac{-a_1\mathrm{s}(\theta_3-\theta_1)[a_4\mathrm{s}\theta_4 + b_4\mathrm{s}(\theta_4+\beta_4)]\delta\theta_1 - a_2\begin{bmatrix} a_4\mathrm{s}(\theta_2-\theta_4)\mathrm{s}\theta_3 \\ +\, b_4\mathrm{s}(\theta_4+\beta_4)\mathrm{s}(\theta_3-\theta_2)\end{bmatrix}\delta\theta_2}{a_4\mathrm{s}(\theta_3-\theta_4)} \\
\delta y &= \frac{a_1\mathrm{s}(\theta_3-\theta_1)[a_4\mathrm{c}\theta_4 + b_4\mathrm{c}(\theta_4+\beta_4)]\delta\theta_1 + a_2\begin{bmatrix} a_4\mathrm{s}(\theta_2-\theta_4)\mathrm{c}\theta_3 \\ -\, b_4\mathrm{c}(\theta_4+\beta_4)\mathrm{s}(\theta_3-\theta_2)\end{bmatrix}\delta\theta_2}{a_4\mathrm{s}(\theta_3-\theta_4)}
\end{aligned} \tag{2}$$

where s and c stand for sine and cosine. Substituting Eq. (2) in Eq. (1) we get

$$\begin{aligned}
T_1 &= \frac{a_1\mathrm{s}(\theta_3-\theta_1)[a_4\mathrm{s}(\theta_4-\phi) + b_4\mathrm{s}(\theta_4+\beta_4-\phi)]}{a_4\mathrm{s}(\theta_3-\theta_4)}F_{04} \\
T_2 &= \frac{a_2[a_4\mathrm{s}(\theta_2-\theta_4)\mathrm{s}(\theta_3-\phi) - b_4\mathrm{s}(\theta_3-\theta_2)\mathrm{s}(\theta_4+\beta_4-\phi)]}{a_4\mathrm{s}(\theta_3-\theta_4)}F_{04}
\end{aligned}$$

3.2 Design Optimization

The 5R mechanism is simulated using Microsoft Excel® using the kinematic and force equations given in Sect. 3. When the end effector is grasped by a user, we aim to achieve uniform feeling throughout the workspace. Assuming a constant force along the x-direction (direction of major motion of hand while writing) acting on

Table 1 Designed link lengths

a_0	b_0	c_0	d_0	a_1	a_2	a_3	a_4	b_4	β_4
250 mm	50 mm	117.5 mm	50 mm	200 mm	250 mm	250 mm	250 mm	60 mm	60°

the end-effector, the motor torque requirements are computed and drawn as a surface plot on the workspace. The torque surfaces are desired to be as flat as possible. Taking avoidance of link collisions into account, a parametric design is performed by changing the link lengths in order to obtain flat torque surfaces for both of the motors. The optimization criterion is to minimize

$$r = \frac{\max(T_i) - \text{average}(T_i)}{\text{average}(T_i) - \min(T_i)}$$

where T_i for $i = 1, 2$ stands for the torque of the motors. An optimal solution is obtained by manually changing the link lengths in Excel®. Designed link lengths are given in Table 1. Torque requirements for a constant force of 1 N at the end-effector are given in Fig. 2. Accordingly, one of the motors demands 0–0.18 N m, while the other one demands –0.21 to 0.05 N m. Ratio r is ~0.86 for both motors.

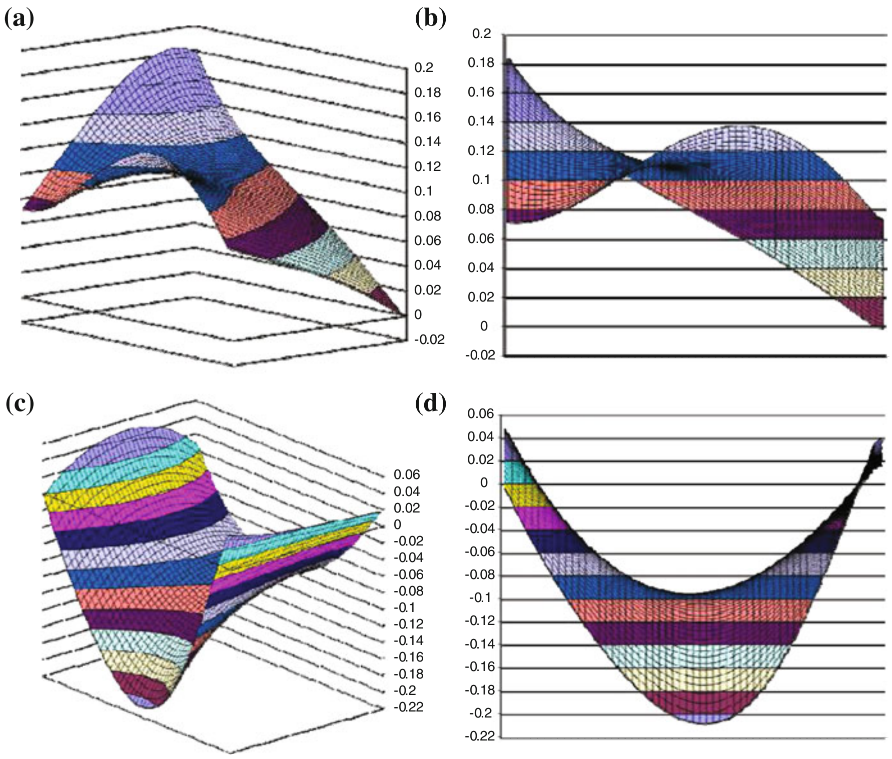


Fig. 2 Torque requirement of the motor at joint A_0: **a** auxiliary, **b** side views; torque requirement of the motor at joint B_0: **c** auxiliary, **d**

Minimizing the ratio r corresponds to optimizing the mechanical advantage throughout the workspace of the mechanism. It is well known that the mechanical advantage is lost when the mechanism is positioned near singularities. So, optimizing r also guaranties that the mechanism is far from the singular configurations as well.

It is also possible to apply numerical optimization techniques to obtain optimal dimensions for the mechanism. We did not formulate the problem as a constrained optimization problem for several reasons. First of all, there are 10 design parameters (see Table 1), which means that the optimization should be applied on a 10 dimensional space. The dimension of the optimization space can be reduced by assuming some of the parameters, but running the optimization algorithm for different assumed values is very time consuming. Also, the objective function should include all design criteria with well-chosen weights of the criteria, whereas with parametric design in Excel®, we monitor the ratio r, the variation of both of the motor torques over the workspace, possible link collisions and ergonomics of the design at the same time. Since everything is evaluated and printed on screen in the blink of an eye, Excel® enables a quite fast and intuitive design environment.

4 Constructional Design

The constructional design of the device is performed in CAD environment. The main concern in choosing link material is to obtain higher strength to weight ratio at links. In this way, the minimum impedance of mechanism will be as low as possible by having the smallest inertia properties. The maximum impedance that can be simulated by the mechanism should be as high as possible as well. In that case, the link rigidity receives importance.

Joints structure is also important since for a high precision application minimum joint clearance is required. In addition, in designing impedance type of haptic devices, another important issue is minimization of joint frictions to increase the transparency of the device, which is the desired to displayed impedance ratio. In order to have lower joint frictions, two ball bearings per joint are used for bedding and they are housed by Aluminum parts to minimize the joint clearance by having acceptable rigidity while having relatively low weight.

The assembly of the device is done in such a way that the control card and the power supply do not collide with the links at any instant of manipulation. Manufactured and assembled handwriting mechanism is shown in Fig. 3.

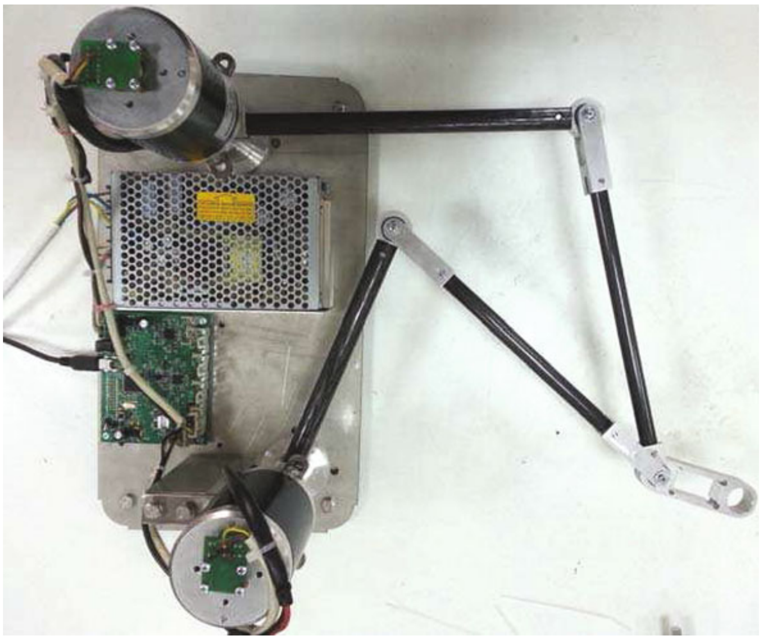


Fig. 3 Constructed and assembled first prototype

5 Conclusions and Discussions

Haptics technology has found application in various areas to provide a solution for different needs. This study aims to make use of this technology for providing assistance in learning handwriting skills. In this paper, work carried out for designing the mechanism of the handwriting assistance device is described. First the kinematic and force equilibrium equations are derived. Then the system is simulated and link lengths are determined in order to optimize force exertion characteristics.

There still remains some more work to do in this research. The design for the pen to be attached at the end-effector is to be carried out. The vertical motion of the pen for writing and traveling modes is to be achieved by means of a solenoid actuator. The electronic hardware for communication between the device and a computer and driving the motors is designed and manufactured and the software is still being developed. The experimental tests will be performed when the overall design is completed.

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