A Miniature Tactor Design for Upper Extremity Prosthesis

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Abstract

We have been developing a miniature haptic device - a tactor - that can display pressure, vibration, shear force, and temperature to the skin of upper extremity amputees, especially those who have undergone targeted nerve reinnervation (TRI) surgery. In TRI patients, regions of the reinnervated skin are perceived as being on the phantom hand. This paper presents the mechanical design of the tactor.

1 INTRODUCTION

Haptic (touch) feedback is critical in many activities of daily life. For example, when we manipulate a cup of water, we use a sense of grip strength as well as incipient slip in order to keep from crushing the cup or letting it slip. Similarly, people can discriminate among materials using the sense of vibration, shear force and temperature. A principal goal of our research is to provide upper extremity amputees with these same capabilities. Thus, as a component of a larger effort aimed at restoring haptic sensation to those who have lost an arm or hand, we are exploring the display of the sense of touch.

This paper is most relevant in the context of patients who have undergone “targeted reinnervation” (TRI) surgery [1–3]. TRI creates sensory spots on a patient’s skin (for instance, the chest or upper arm) that are perceived as spots on the skin of the phantom hand. Thus, by placing sensors on the prosthetic hand and using these to command tactors on the TRI skin, it should be possible to create a realistic sense of touch.

We are developing a multi function tactor which can display the sense of pressure, vibration, shear force, and temperature, simultaneously. In this paper, we will describe our approach to the mechanical design of the tactor. Here, we address first the development of a design specification, second the electromechanical and mechanical design of a tactor that meets the specification.

2 Design Specifications and Performance Requirements

Because haptics comprises such an extraordinarily rich set of sensory pathways, it was important for our team to prioritize those which we wished to restore. Discussion among team members1 led to the following prioritization.

First and foremost, we seek to restore the sense of contact with an object. This sense provides “goal attainment” information which is critical in multi-finger grasping. Second, we seek to restore the sense of pressure, which is critical in adjusting grip strength. Third is vibration, which is essential in discriminating among different textures. Fourth is temperature, which is both useful in materials identification, and also for social reasons: amputees often indicate the desire to feel the warmth of a loved one’s touch. Fifth, is shear force, which is important in detecting slippage and in materials identification. Shear is especially important in discriminating slippery from sticky materials. Finally we seek to restore fine shape discrimination, such as the ability to feel and edge, separate sharp from dull, or "read" a set of Braille dots. In the work presented here, we explicitly address the first three goals as well as the fifth. As stated above, temperature is discussed elsewhere.

At the outset of this project we did not have quantitative specifications for any of the goals above. To establish these, we began by building an “experience prototype.” The experience prototype, shown in Figure 1, was in no way intended to meet packaging, weight or power consumption requirements (discussed below), but was intended to apply forces and motions to an intact fingertip in response to

1We wish to acknowledge Prof. Ronald Johansson, members of Prof. Paolo Dario’s Cyberhand group and Prof. Allison Okamura
Table 1. Mechanical Performance Requirements of a Tactor

<table>
<thead>
<tr>
<th>Specification</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Force</td>
<td>9.0N</td>
</tr>
<tr>
<td>Resolution of Force</td>
<td>0.1N</td>
</tr>
<tr>
<td>Max. Velocity</td>
<td>40cm/sec</td>
</tr>
<tr>
<td>Max. Acceleration</td>
<td>4.0G</td>
</tr>
<tr>
<td>Workspace</td>
<td>10.0mm in vertical direction</td>
</tr>
<tr>
<td>Pressure</td>
<td>8.8N peak for an 8.0 diameter tactor head</td>
</tr>
<tr>
<td></td>
<td>50% beyond discomfort threshold</td>
</tr>
<tr>
<td></td>
<td>0.1N</td>
</tr>
<tr>
<td></td>
<td>0.15 - 0.20N JND</td>
</tr>
<tr>
<td>Vibration</td>
<td>Support pad area 10 times larger than tactor head to avoid discomfort</td>
</tr>
<tr>
<td>Tapping</td>
<td>40cm/sec, 4G</td>
</tr>
<tr>
<td>Vibration</td>
<td>2.5 cm/sec, 1.6G max. (Fig.2)</td>
</tr>
<tr>
<td>Power</td>
<td>less than 2.8 watt-hour in ADL</td>
</tr>
</tbody>
</table>

The experience prototype was used to measure force and motion associated with pressure, tapping (the type of contact most demanding of tactors), and vibrations associated with rubbing across various surfaces including ribbon cable and sandpaper. The vibration data was used to establish amplitude requirements as a function of frequency, which are summarized in Fig.2. Note that these are not threshold data, as are often reported, but are instead data representing the largest amplitudes required at each frequency. We found, however, that tapping demanded more of the tactor than vibration. Tapping required speeds of 0.4m/sec, acceleration of 4G’s, and forces of nearly 2N.

Pressure data from Sensinger and Weir indicated that one TRI patient began to feel discomfort at 5.8N normal force and pain at 8.8N, corresponding to skin penetration of about 10mm [4]. This same subject had a normal force JND of 0.15 – 0.2N. To ensure adequate range, we set the tactor maximum force specification at 9.0N, and the stroke at 10mm. In order to ensure safety, software and hardware limits will be used in practice.

Table 1 summarizes the key performance specifications. In addition, we discovered that it was preferable for the tactor head to move straight down into the skin rather than follow a rotary path, and we found by trial and error that a tactor head about 8.0mm in diameter provided a good trade-off between power (better for smaller heads) and comfort (better for larger heads).

A number of other constraints were placed on the design. The tactor was allocated a power budget of 2.8 Watt-hours; however, the actual power expenditure will ultimately depend on usage. While estimates of tactor usage in “activities of daily living” have been made, they will not be discussed here. The light tactor mass was required, and a compact sensor (load cell, accelerometer) readings such that the motions, forces and power associated with various sensations could be measured. It unfortunately did not prove practical (from a scheduling standpoint) to take this data with TRI patients. However, we were able to take advantage of data taken by Sensinger and Weir with a TRI patient establishing peak force and displacement requirements.

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profile was sought for aesthetic purposes. Ease of donning and doffing were required, as well as resistance to spills and sweat. Finally, we should note that multiple tactors - for instance, on for each fingertip and on for the palm - is ultimately desired.

3 Mechanical Design

A variety of different overall design approaches were considered. For instance, an option would have been to build separate systems for pressure and vibration. This was in fact considered, but was eliminated when it became apparent that the requirements for tapping essentially enveloped those of both pressure and vibration. Invasive or aggressive designs (e.g., those involving skin piercings) were also eliminated. Eventually, we settled on a tactor that is essentially a small two degree-of-freedom robot: one degree-of-freedom for normal force (also tapping and vibration), and one for shear force. In this section, we review actuator selection, linkage design, and sensor selection/design.

3.1 Actuator Selection

While a number of different types of actuators were considered, it became apparent that rotary electromagnetic motors and gearboxes would be the best choice, at least for a first generation design. We selected the MAXON 10 mm diameter RE10 DC brushed motor, which has a peak mechanical power output of 1.5 watts. We also selected a 16 : 1 planetary gearhead resulting in a maximum torque of 51.8 mNm, which proves sufficient as will be explained in the next section. Because the motor has a relatively high no-load speed of 12500 rpm, there is no problem meeting the speed requirements.

Although this motor meets our specification, there are good reasons to continue exploring actuator alternatives. The 10 mm diameter of the motor, while small, may need to be reduced further. The planetary gearboxes have considerable backlash, which limits frequency response. And the connectors to the motor’s optical encoder are prone to failure. Brushes are also a known reliability issue. Despite these challenges, these motors have worked well in tests to date.

3.2 Mechanism Design

As mentioned above, our design incorporates two degrees-of-freedom, including pressure and shear. In addition, we felt it important to keep the tactor head parallel to the skin surface at all times. It actually simplifies the design to lift this requirement, and we have also developed tactors for which the head rotates slightly as it moves side to side (in shear). Those will be discussed in another paper.
Figure 5. Required torques to create 9.0 N force in y direction: (a) of the actuator 1, (b) of the actuator 2. The white region is the actual workspace of the implemented tactor.

We considered a variety of mechanism designs for converting two actuator outputs to two translations of the tactor head, and ultimately settled on a 6 bar mechanism with two skewed parallelogram linkages (Fig.3). Because it involves no gears or sliding joints, this mechanism is low in both lost motion (e.g., backlash) and friction. Moreover, the skewed parallelograms help to maximize the workspace of the tactor by minimizing the singularity region as shown in Fig.4.

The mechanism’s kinematic properties such as workspace and manipulability are determined by the lengths of the links. In order to find link lengths, we developed a MATLAB toolbox that displays the kinematic properties. Before determining absolute link lengths, an iteration is performed to find the optimal link length ratios for $l_5$, $l_1$, $l_2$, and $l_e$ in Fig.3. The link length ratios that minimize the condition number (which we use as a manipulability index) across the workspace are determined to be $l_1/l_5 = 0.5$, $l_2/l_5 = 0.8$, and $l_e/l_5 = 0.5$. Thus, the absolute value of link lengths can be determined by the specification of the required workspace in Table 1 and the minimum distance between active joints, $q_1$ and $q_5$, as $l_5 = 12.0$, $l_1 = 6$, $l_2 = 9.6$, and $l_e = 6.0$. The manipulability plot of the tactor in the workspace is shown in Fig.4. Except at the workspace boundaries, the tactor has a condition number less than 5.0, which leads to reasonably isotropic motion and force.

Fig.5 shows the required torques to create 9.0 N of normal direction force. The results indicate that the necessary torques are less than the maximum torque of the selected actuator, 51.8 mNm, in most region of the workspace.

Since the tactor contains closed kinematic loops, it is necessary to consider over-constraint problems caused by joint axes that are misaligned during assembly or manufacture. We used carefully selected bearing configurations to avoid the over-constraint problem. For instance, in Fig.6 consider the closed loop of $J_1-J_2-J_3-J_{11}-J_{10}-J_9$. Normally, one would use two bearings at each of these joints to ensure pure revolute behavior and no off-axis wobble. Doing so in a closed loop, however, virtually guarantees binding due to over-constraint. Instead, we used only a single bearing at joints $J_{11}$ and $J_9$. This allows enough off-axis wobble to resolve the over-constraint while still preventing any wobble of the tactor head itself (the link connecting $J_3$ and $J_{11}$). Similarly, for the closed loops of parallelogram $J_1-J_7-J_9-J_6$ and $J_7-J_8-J_{10}-J_3$, single bearings are used for the joints of the triangle part ($J_7-J_8-J_9$) to resolve over-constraint.

In order to realize the proposed mechanism, we used the miniature bearings (3mm(OD) / 1mm(ID) and 5mm(OD) / 2mm(ID)) and precision-machined linkages. Fig.7 shows the tactor mechanism. Link collisions and assemblability had to be carefully considered. As realized, the tactor has the workspace shown with dotted lines in Fig.4. The workspace is 10mm up and down and, at maximum, 12mm side to side.
3.3 Force Sensors

A 2DOF force sensor is required for the closed loop control of pressure, vibration, and shear force. The tactor head is an ideal sensing location, but a thermoelectric device is also placed on the tactor head for thermal display, and the associated thermal gradients can be expected to cause significant sensor drift. An alternative is to measure the torques output by the motor/gearboxes and compute the force at the tactor head using the conventional torque to force mapping. However, since, to the best of the authors’ knowledge, there are no commercially available torque sensors that satisfy the design constraints/specifications, we set out to design custom sensors.

Our torque sensor design is illustrated conceptually in Fig. 8. The sensor involves an in-line flexure, but with strain gages arranged to measure shear force. This has the advantages of small size, simplicity, and relatively high immunity to disturbance forces. It has the disadvantage of requiring moving cables; however, due to the limited rotation of the shafts, this has not posed a great difficulty.

The smallest COTS gage that we were able to find for shear stress was the VISHAY 015EH [5], which limited the size of the sensing parts to $2.76 \times 5.10$. Titanium is used to maximize the yield strength and the sensitivity of the torque sensor. Using MATLAB FEM toolbox, the flexure was sized to ensure that the maximum stress on the torque sensor is less than 20,000psi under 50.0mNm applied torque. Since titanium has 0.2% yield strength of 150,000psi, we are confident that no actual damage will occur in operation. Fig. 9 shows the torque sensor as manufactured by Sensing System Co. [6] which has the sensitivity of 3.25mV/V and the maximum torque capacity of 50.0mNm.

4 Concluding Remarks

According to the specification of the tactor that was built at the outset of this research, we have been developing a multi-function tactor that is able to provide contact, pressure, vibration, shear force, and temperature feedback to upper extremity amputees, especially those who have undergone TRI surgery. Our design uses a closed loop 6 bar mechanism with skewed parallelogram linkages to provide normal and shear motion while keeping the tactor head parallel to the skin surface. The tactor also achieves the following characteristics: i) workspace maximization subject to good manipulability; ii) size minimization through careful linkage design and close-tolerance machining; iii) a unique bearing configuration to avoid over-constraint; iv) customized torque sensors for closed loop force control. The result is a small, light weight and wearable device.

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myoelectric prosthesis control in a bilateral shoulder disarticulation amputee.”

