A Multimodal Haptic Mouse for Visually Impaired People

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Abstract

This work describes early research activity on a haptic mouse interface. This project aims to join tactile and kinesthetic feedbacks in order to improve the accessibility of the PC to visually impaired persons. In this phase a planar haptic interface has been developed. It is based on two linear motors, which allows a simple mechanical structure, with high stiffness and without backlash. The system is backdrivable but to reduce the friction effects and therefore enhance its transparency, the device has been equipped with a load cell along each axis. A suitable controller exploiting a force loop has been developed and some significant tasks experimentally verified. In particular, since this haptic mouse will be applied to interact with graphical user interfaces, the tracking of predefined paths and the rendering of geometrical shape have been tested.

1 Introduction

Visually impaired people can obtain great advantages from the use of haptic devices. As a matter of fact, for such a category of persons the touch is the main cognitive channel to explore the external world. For this reason, in the last decade, a number of innovative haptic systems or research activity involving haptic devices have been proposed with the specific aim to support blind persons [1, 2, 18, 17]. Beside acoustic/vocal signals, haptic devices seem the more natural way to construct an interface between blind users and personal computers, whose role in the fields of education, entertainment, social relations, work, is becoming more and more important. On the other hand, computer environments are much more complex than they ever were before, because of the adoption of graphical user interface and the consequent combination of of textual and pictorial/symbolic representations.

A number of projects have attempted to make access to the PC more straightforward for blind operators. With respect to the sense of touch, it is possible to recognize two main groups of tools: on one hand devices providing cutaneous/tactile sensations, on the other hand robotic systems able to apply to the user kinesthetic feedback. To the former group belong all the devices derived from the original idea of the Optacon (Optical to Tactile Converter) [3], which transformed a printed material (in particular a printed letter) into a tactile image through a matrix of pins, able to individually vibrate. Examples of similar devices (purposely designed for PC access) are the arrays of (40-80) braille cells which enable blind users to read a plain text (through a translation in braille code) or the VirTouch Mouse [4], a commercially available device which integrates the function of a regular computer mouse with three tactile displays (each incorporating 32 rounded pins arranged in a four by eight matrix), providing the user with a tactile translation of the screen zone immediately close to the mouse pointer, and allowing the recognition of graphic shapes, diagrams, mathematical graphs, etc..

The latter category of devices for aiding blind persons includes a number of systems, which allow to explore 2D or 3D spaces, providing forces (and in some cases also torques) to the user [1]. Noteworthy devices belonging to the planar haptic device family are the Panthograph [5] and the Moose [6] while to explore a 3D environment the most encountered interface is the Phantom [7] by SenSable Technologies, a general purpose 6 dofs haptic interface often employed to develop applications for visually impaired people.

To the knowledge of the authors, the integration between the two perception modalities tied to the touch, that is tactile and kinesthetic, has been addressed only in few research activities. In 1994, Akamatsu [8] proposed a
multimodal mouse with force and tactile display, but in this case the tactile feedback was limited to a single vibrating element placed on the left button. Two years later, Ramstein [9] combined Haptic and Braille technologies and performed a number of experiments with the goal to estimate the potentiality of this technology with respect to traditional ones. More recently, Yang et al. [10] have developed a mouse able to provide force feedback and vibration (through a matrix of pins) to be used as a test-bed in psychophysical study on tactile perception.

2 A mouse with force and tactile display capabilities

The idea underlying the overall project is to study the interaction between force and tactile display in a unique system which could be used as input/output device for the exploration and interaction with common computer applications. As pointed out in the Introduction, the fusion of different haptic sensations in the same device has been only slightly considered, at least in the field of assistance of visually impaired persons. Conversely, it is worth noticing that force/kinestetic feedbacks and tactile stimuli are not only related but they provide complementary information. The former ones enable to feel virtual objects through a pointwise feedback related to the interaction between the virtual point (commanded by the human operator) and the surface of the explored object [7]. For this reason the systems based on this approach are useful to determine the large scale shape of objects by means of a dynamic exploration, while the single point contact, which the most part of this devices allows, limits the cutaneous feedback and the possibility to sense some important tactile information such as textures and small scale characteristics of the surface.

On the contrary, tactile systems affect the skin surface of the user, by stretching or by pulling it, through a contact which commonly involve an “extended” portion of the operator’s skin and not a single point. In this way, it is possible to perceive the characteristics of an entire area of virtual objects’ surface, such as the local curvature or the texture, or others features properly converted into cutaneous stimuli (i.e. the braille translation of one or more letters). The main limitation of tactile devices is their capability to provide information, although very detailed, extremely localized on a limited area around a point of interest, while a global “vision” results quite difficult.

This project aims to integrate both these approaches in order to overcome the limitations of each one and to enhance the capability of the user of exploring a virtual environment. In particular, since our attention is focused on the computer accessibility of blind persons, a 2-dimensional I/O device, which could substitute a standard mouse, is considered. The system will be composed by two main parts:

- an haptic platform, free to move on a plane and capable to provide the human operators with a force feedback (mouse with force feedback);
- a tactile subsystem, located on the top of the mouse, formed by a matrix of pins; in a first phase of the project, a set of piezoelectric braille cells will be used. As a matter of fact, braille cells are commercially available and remains the main “tactile” tool for a visually impaired persons for reading a text. Moreover, their size is perfectly compatible with the dimensions of a mouse and can be easily integrated on it, see Fig. 1.

2.1 Planned activity

The development of the haptic device is only the first step of a complex activity, whose goal is to study and optimize the interaction between force and tactile feedbacks according to the needs of blind persons. There are many possibilities. The most straightforward application is the use of this special mouse for reading texts. In this way, a classical braille display, composed by an array of braille cells which converts an entire line of text into the corresponding braille configuration, can be substituted by this device which leads the user along a line while he is moving for reading through the tactile displays. That can be easily obtained by applying to the text to be read a field of virtual forces attracting the user towards the line, as it is shown in Fig. 2, where the potential energy associated to such a vector field is shown.

In [9] Ramstein demonstrated that the performances achievable with two moving braille cells mounted on a planar force feedback device are lower that those attainable through large braille displays (with 40 or 80 cells).
A different haptic devices (based on a different structure and control modalities) and a larger number of cells (and of characters displayed at the same time) could improve such results.

Moreover, it is worth to better evaluate the functional capabilities of this device, whose flexibility of use is greatly improved respect to standard braille displays and standard mice. In particular the haptic feedback solves the main problem that visually impaired users encounter by using a standard mouse, that is the lack of a fixed reference frame. The definition of a proper force vector field enable the user to read through the tactile display while he is moving in a structured and friendly environment.

Moreover, an important possibility offered by the proposed device is to perceive at the same time different types of information which are related, i.e. the shape of a geometrical curve and some data associated to it (e.g. the name of the represented signal).

Finally, another important aspect of this research activity, is the analysis of the contemporaneous use of force and tactile feedbacks for rendering geometrical shapes. As a matter of fact the main limitation of vocal synthesis is related to the impossibility to translate a geometrical information, and in this field the use of tactile/kinetostatic devices seems irreplaceable. On the other hand, the way to represent such information is still debated. By means of the proposed device we want to represent graphs, planar figures, schemes (which may incorporate textual and graphical data), etc. in an integrated way which may allow a global but detailed "vi-sion", exploiting both tactile and force feeling.

3 The setup

In this phase of the project, only a prototype of the 2dof haptic mouse has been developed and experimentally tested.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak force</td>
<td>33 N</td>
</tr>
<tr>
<td>Continuous force</td>
<td>9 N</td>
</tr>
<tr>
<td>Max accel.</td>
<td>280 m/s²</td>
</tr>
<tr>
<td>Max velocity</td>
<td>2.4 m/s</td>
</tr>
<tr>
<td>Slider mass</td>
<td>118 g</td>
</tr>
<tr>
<td>Position resolution</td>
<td>1 µm</td>
</tr>
</tbody>
</table>

Table 1: Performances and features of linear motors.

3.1 Mechanical arrangement

The device has a cartesian structure. The main difference with respect to planar haptic systems so far designed is the use of linear motors. The adopted actuators (P01 – 23 × 80) are produced by Linmot® [11] and consist of two parts: a tubolar stator and a cylindrical slider. This actuation modality greatly simplify the mechanical structure of the system and is characterized by performances, which are suitable for the present application. Table I summarizes the features of the motors: the maximum and continuous forces are perfectly compatible with the need of resisting to the force applied by a human operator and they do not require the introduction of mechanical reduction/amplification systems. Moreover, because of the high speeds/accelerations provided by the motors, the system is able to follow even fast movements and the transparency results very good. Being the motor directly connected with the load (respectively the second motor and the mouse) the overall stiffness of the mechanical structure results very high (the most compliant elements in the actuation chain are the load cells). As a consequence, the maximum stiffness that the user can perceive, which is given by the cascade of the mechanical stiffness and of the stiffness due to the control, is practically unbounded (with respect to the purpose of this device, that is to perform haptic interaction with humans) and is equal to the stiffness of the virtual environment. Moreover, the high resolution (1 µm) of the position sensor embedded in the motor, allow to achieve such high values of the virtual stiffness without encounter stability problems [12]. Finally, the direct actuation limits the friction of system and, since the motors are backdrivable, also the overall device will be. However, to further improve the transparency of the haptic mouse during the application of small forces and during free motions in space, each motor is equipped with a load cell (characterized by a structural stiffness of 242.000 N/mm, and an overall weight of 11g), directly connected to the slider, which measures the applied axial force. The system is based on the serial connection of two modules (composed by a motor and a load cell) disposed along orthogonal directions, see Fig. 3. In or-

Figure 2: Force vector field overlapped to a text.
order to sustain the second motor, connected to the slider of the first one, the stator has been located on a linear bearing, while the tip of the movable rod is linked to a standard mouse.

With this architecture, the achieved workspace, which depends on the length of the slider\(^2\), is 110mm × 110mm. Because of its cartesian structure, the haptic devices is able to apply the forces in an isotropic way in the whole workspace.

### 3.2 Control architecture

The controller of the haptic mouse has been implemented at 1 kHz on a standard PC (a Pentium 4 at 1.8 GHz) running RTAI-Linux [13], which provides the motor power electronics (performing the basic current/force control) with the desired force set-point and acquires the encoder and force sensors signals through an I/O board, i.e. the Sensoray 626 (see Fig. 4). It is a low cost PCI analog and digital I/O Card with four 14-bit D/A outputs, sixteen 16-bit differential A/D inputs and six encoder channels.

The operating system provides realtime functionality both in the kernel and in the user space and it supports IPC mechanisms like semaphores, FIFOs and shared memory. These functionalities are used to build a kernel module for realtime control algorithm and to implement monitoring tasks and user interfaces in standard user space. Moreover, the use of a standard PC equipped with a realtime version of Linux makes straightforward the interfacing with the desktop environment and with available applications. As a matter of fact, the availability of open source software, makes it possible to easily customize the applications in order to exploit the proposed device according to the needs of visually impaired persons.

In this early phase of the project, the attention has been focused on the low level control of the haptic interface, that is the control of the interaction between the operator and a virtual world. Being the system a planar cartesian robot, with the two \((x, y)\) axes completely decoupled, it can be modeled as\(^3\)

\[
M\ddot{p} + F_f = F_d + F_o \quad (1)
\]

where \(p = [x, y]^T\) is the coordinates’ vector, \(M\) is a diagonal matrix depending on the masses of the mechanical structure (mainly slider and load cell), \(F_f\) represents friction terms including viscous phenomena and stiction, \(F_d\) and \(F_o\) are respectively the forces applied by the motors and those exchanged with the operator along the directions \(x\) and \(y\). Since the motors are backdrivable, an impedance controller [14, 15], whose parameters depend on the virtual environment, has been implemented by coupling (1) with a simple impedance [16] (see Fig. 5) expressed by:

\[
F'_d = -K(p) - B(\dot{p}) \quad (2)
\]

where \(B(\cdot)\) is the damping term and \(K(\cdot)\) is an elastic function, defining the static behavior of the desired impedance, and, as a consequence, of the overall systems. Such an elastic term, whose expression can be nonlinear, is determined by imposing an elastic potential, whose shape depends on the task to be performed (as reported in the next section). The damping function,

\[^3\]the Jacobian matrix is \(J(q) = I_2\).
which assures the stability of the system, is assumed to be a linear function of the speed $B(p) = B\dot{p}$ with $B$ symmetric square matrix.

Additionally, in order to compensate for friction terms in (1) and eventually the inertial ones, an inner force controller (based on the force $F_o$ measured by the two load cells) has been performed along each direction. Since a high gain loop is needed to reduce the force error, but, in the other hand, a simple proportional controller amplifies the electric noise affecting the force signal and produces a vibrating behavior, an integral term has been adopted. Finally, in order to limit the effects of phase lag introduced by the integral action, which is perceived by the operator like an inertial term, the contribution of the PI controller has been saturated and an anti-windup mechanism implemented. In this way, the force controller is able to compensate the static friction and other undesired dynamic phenomena even if the contribution of (2) is small or null (motion in free space) and guarantees in this way the transparency of the haptic system. On the contrary, when the user encounters an obstacle in the virtual environment (and accordingly the force applied by the system grows), the main control terms is given by (2), which does not rely on the force controller, and provides an instantaneous response, directly related to the desired impedance and not influenced by the delay of the integral term.

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4 the stiction threshold is about 3$\text{N}$ but it is variable, depending on the motor position.

4 Early experimental tests

In order to verify the performances of the mechanical structure and of the adopted control approach, and to evaluate the functional capabilities of the device, some simple tasks have been accomplished. Since the main purpose of this system is to assist the human operator in tracking predefined paths (mainly straight lines), or to recognize the shape of geometric elements, the following tests have been considered:

1. free-space motion;
2. tracking of straight lines;
3. interaction with a continuous curve (circle);
4. interaction with a polygonal shape (square).

The first task should demonstrate the transparency of the device when no interaction with the virtual environment occurs: the force that the user must apply to move the mouse in free space is smaller than 0.5$\text{N}$. The task 2) is relevant for the translation of textual matter into braille code which a visually impaired person could read through the mouse itself. As a matter of fact, as reported in subsection 2.1 the user must be aided to follow a text line while the tactile displays incrementally translate the text characters. Since the aim is to rapidly explore a document, possibly skipping from different lines or parts of text, the operator must be free to follow the text line or to change it. For this reason the elastic potential associated to this task is the one shown in Fig. 2: the potential is constant in the $x$ direction (in this manner, no force is produced along this direction) while along the $y$ direction it is a raised sine, whose spatial period is equal to the distance between two text lines. In this way the operator feels a growing force while is moving away from the potential minimum, and he is led along the line. In any case, he can easily change the line by applying a small force, obviously larger than the maximum of the potential energy. Results corresponding to this task are reported in Fig. 6.(a) where the followed path (measured position) is reported together with the forces applied by the operator. From the figure it is evident that the tracking of a straight trajectory is very good and that the main component of the measured force is directed along the normal direction to the line.

Since the structure of the mouse is characterized by two preferential directions (coincident with $x$ and $y$ axes), in order to test its performances, the task 2 has been replicated by considering the straight lines oriented along a general direction, see Fig. 6.(b). Also in this case, the same potential function but with a different orientation is used, and the user is able to follow the desired path.
with still a good precision.
It is worth to notice that these are simple examples, only useful to probe the robotic device, but the shaping of potential energy of the elastic term will require deeper investigations, in order to improve the functionalities provided by the systems with respect to the necessities of blind persons. For instance, in this second task, the constant potential along the text line can be replaced by an elastic energy which enables the user to recognize single characters.

Since the main goal of the project is to study the most convenient way to reproduce geometrical shapes and contours through tactile and kinesthetic feedbacks, the last two tasks have been arranged as follows. In the former the potential energy of the virtual environment has been shaped as shown in Fig. 7.(a), that is with the minimum along a circular trajectory. In this way the mouse is “constrained” to remain on this virtual path and the user can perceive the corresponding shape, see Fig. 7.(b).

Also in this case, a circular trajectory has been chosen for sake of simplicity, but more complex curves can be adopted, e.g. a line in a generic graphic.

In the last tasks, the potential energy has been assumed constant within a square area while it is increasing in a narrow stripe close to the border, see Fig. 8.(a). In this way, as reported in Fig. 8.(b), the user can feel the perimeter of the square through a force which tends to push away the mouse towards the center of the area, where the operator can freely move. From Fig. 8 it comes out the high precision of the device in rendering the shape of this polygonal object in both linear edges and angles.
5 Conclusions

In this work, a research activity on an haptic mouse interface is reported. This project aims to join tactile and kinesthetic feedbacks in order to improve the accessibility to the PC of visually impaired persons. It is worth to underline that this is only the first phase of the research activity, and that at the moment only the planar haptic interface has been developed. It is based on two linear motors, which allowed to design a very simple mechanical structure, based on a cartesian architecture, with high stiffness and without backlash. The system results backdrivable but to reduce the friction effects and therefore enhance its transparency, the device has been equipped with a load cell along each axis. A suitable controller exploiting both the backdrivability of the system and an inner force loop has been developed. In order to test the functional capabilities of the devices with respect to the proposed purpose of assistance of blind people, some significant tasks have been experimentally verified. In particular, since this haptic mouse will be applied to interact with Graphical User interfaces, the tracking of predefined paths and the rendering of geometrical shape have been successfully tested. The next step will be the integration on the system of tactile displays to perform tasks, such as the translation of text lines pointed by the mouse into braile code, and to improve the rendering of virtual objects. Test with visually impaired persons are then planned.

References


