Improving manual skills in persons with disabilities (PWD) through a multimodal assistance system

Mario Covarrubias, Elia Gatti, Monica Bordegoni, Umberto Cugini, and Alessandro Mansutti

KAEMaRT Research Group, Department of Mechanical Engineering, Politecnico di Milano, Italy

Received 22 October 2012
Revised 6 March 2013
Accepted 21 March 2013

Introduction

This article describes a Multimodal Guidance System (MGS), consisting in a combination of haptic and sound technologies, aiming to be a step forward in the field of multimodal devices for supporting people without skills to improve their skills, and in the assessment of manual activities. Sketching, coloring in and cutting tasks are assisted through the haptic guidance device. The drawn shape can also be physically produced as a piece of polystyrene foam. The cutting operation is performed by using a hot wire tool, which is linked to the haptic device. In addition, several sound metaphors are explored. The objective of this investigation of the multimodal system is to experiment with a new tool that allows people without skills to perform the assessment of manual skills in an intuitive, natural and easy manner. This group of people has demonstrated that with early intervention programs, their possibilities of having a better life are growing as well. Unfortunately, today's practice to assess motion control and skill improvements need to be completed with continuous assistance given by care assistants, so considerably limiting the possibility to exploit the great potential that those people have. However, there is still much more opportunity for developing tools to help and support them for improving both, their productivity and independence in the workplace. This can be done, by providing tools to employers and employees to assist them to maximize the operational capacity. The multimodal system is designed as a tool that supports manipulation and actions needing a very limited support provided by care assistants, for ensuring the integration and independence in the learning environment. Haptic guidance tasks are common in several applications and have been widely analyzed. Trajectory assisted task has a significant value in many applications such as medical

Address for correspondence: Dr. Mario Covarrubias, Department of Mechanical Engineering, Politecnico di Milano, Mechanical Department, Milan, Italy. E-mail: mario.covarrubias@mail.polimi.it

training, hand-writing learning, and in applications requiring precise manipulations. Examples include haptic-guided menu selection [1], handwriting training [2], surgical training [3] and devices that provide robotic-assisted repetitive motion fine-motor training [4]. The guiding force can be either generated by a force-feedback device, such as a Phantom haptic device [5], or simulated by software [6,7]. To evaluate the effectiveness of the multimodal guidance device, several tests have been performed. First, the MGS has been tested by a group of able-bodied people in order to get knowledge about the precision and limits of the device, then the MGS has been tested by people with specific disorders such as Down syndrome and developmental disabilities. This second group of people without skills has been selected because they lack in many of the fundamental skills related to movement precision, coordination of force, speed and reduced efficiency in performance as compared with able-bodied people. One of the hypotheses suggests that the source of motor difficulties originates in deficit of the central nervous system [8], whereas other evidence suggests a peripheral impairment related to hypotonic conditions. Down syndrome is the most common chromosomal condition associated with developmental disabilities. As suggested by the literature [8,9] practice can have positive influence on the motor skill. In case of developmental disorders, such as Down syndrome, motor control may be greatly affected [10]. The manual tasks supported by the MGS include operations as for example sketching several shapes, coloring in the internal area of a shape and finally, cutting funny shapes using foam as material. These manual operations are usually performed in several educational activities inside the learning environment of people without skills.

System description

The MDS allows the initial definition of a set of geometric shapes that the users will draw, and physically produce thanks to the cutting system in an assisted way. Figure 1 provides a schematic view of the system's architecture. The shapes are initially generated through the use of a generic CAD tool. The shapes are saved in the VRML format, which is a standard file format for representing 3-dimensional interactive vector graphics. This file includes the IndexedFace set list, which represents the 3D shape formed by constructing faces (polygons), and the Coordinate point list, which contains the coordinate of each single node that defines the 3D vertices of the shape. Finally, these data are imported in the H3D API software that is used for rendering the haptic guiding path, on the basis of the geometry of the shape.

This software was chosen because it is an open source platform that allows users to handle both graphics and haptic data. The software also allows users to easily manage the Magnetic Surface constraint, which provides a force on the haptic device based on a given distance from a virtual surface. In this way, a snap constraint is applied allowing the user to control and vary the stiffness and damping constraints as needed. The snap distance is a parameter that defines the outward distance for the application of the attracting effect.

Use of the system from the people without skills

As mentioned in the introduction, people without skills are the target group of final user for the haptic guidance device. Taking this into account, the mental load required to use the device should be reduced by means of using a co-located system [11]. The term colocation has been used to describe a haptic and a visual display that is calibrated such that the visual and haptic coordinate systems are coincident. This means that the user can visually perceive an object in the same position in space as the haptic simulation [12]. This criterion simplifies the perception process required from users, and facilitates its natural integration to allow fast reflexive motor responses to the haptic stimuli. In our device, this is achieved by using a 2D printed sketch aligned with the coordinate system of the 2D haptic sketch. The haptic rendering and the control of the haptic device are based on the H3D API platform. Therefore, the geometric model of the virtual sketch and all the necessary physical properties are defined through a configuration file, written in the ''X3D'' format.

Use of the system from teachers and care assistants

In order to gain a rich and accurate description of the impact of the MGD, it is also important in the evaluation to gain information from the teachers and care assistants. Taking this into account, we have designed a Graphic User Interface in order to involve teachers and care assistants during the test phase. In this way, we are also providing some training for the use of the system to the teachers and care assistants.

The data recorded throughout the exercises provide information about the position of the stylus on the working plane, velocity and the time elapsed to complete the exercise.

Haptic rendering and visualization dissociation

In order to obtain an easy and intuitive visualization system for the teachers and care assistants, we decided to dissociate the haptic and the visual constraints. This has been done considering the monitor as the drawing sheet. To make this effect permanent and independent from the uploaded file, the

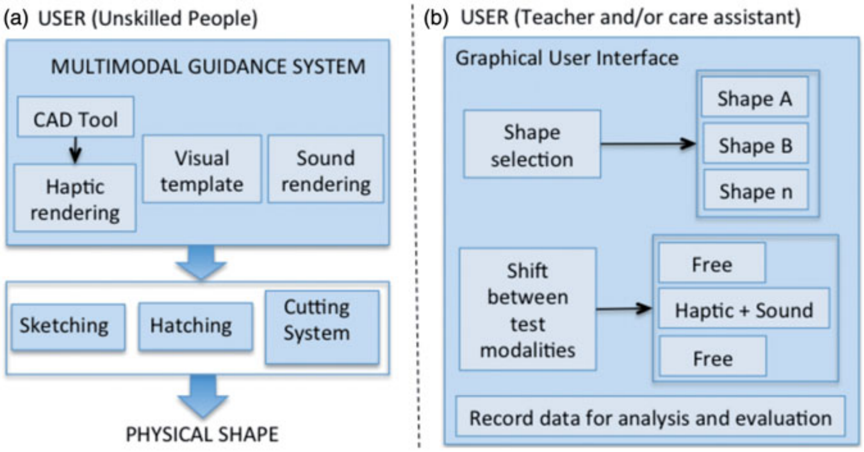


Figure 1. Multimodal guidance system architecture.

Figure 2. The concept of the multimodal device.

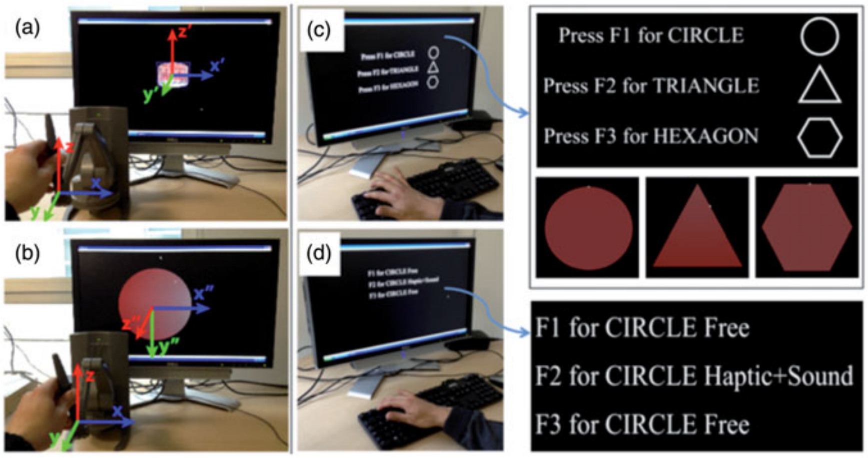
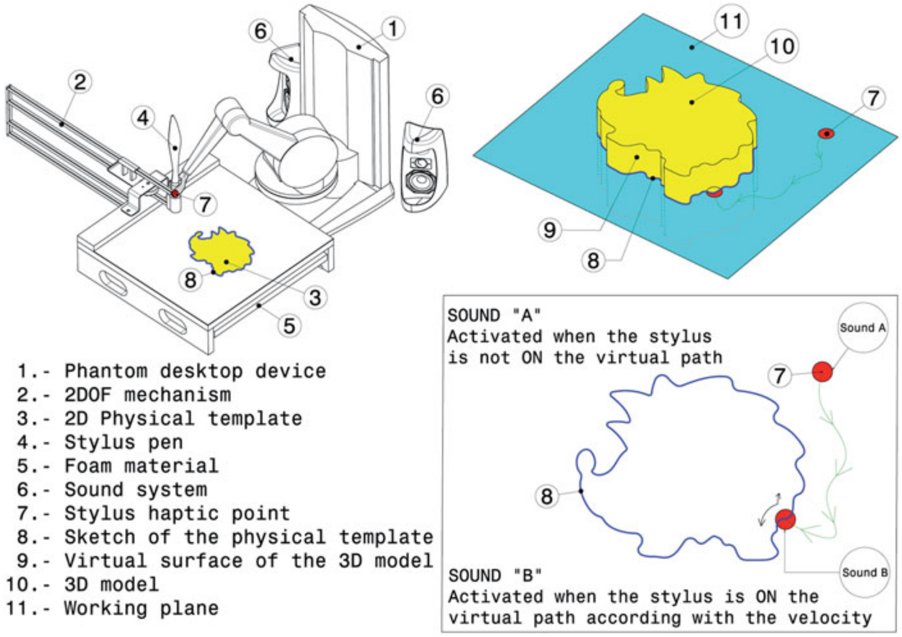


Figure 3. The concept of the robotic and multimodal device.



calibration file of the Phantom haptic device has been modified, in so that the desired configuration file is loaded directly.

With H3D viewer standard settings the frame of reference of the Phantom haptic device and the geometry are equivalent (Figure 2a and b).

The decoupling constraint between haptic and visual coordinates is carried out with a rotation of the frame of reference around the x-axis, as can be seen from Equation 1, thus obtaining that the z-axis of the H3D viewer is orthogonal to the monitor.

$$[A''] = [A'][R_x] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta & 0 \\ 0 & \sin\theta & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

With the teacher's help, we have implemented the test methodology to use for the validation of the device accuracy. Figure 2(c) shows the teacher while using the GUI interface with the first screen asking for the shape selection. We have designed simple and complex shapes, i.e. circle, triangle, hexagon, rectangle, star, etc. The teacher gets a visual feedback of the shape and position of the stylus. If the F1 key is pressed, a circle is activated in order to ask the user without skills to perform the sketch operation; if the F2 key is pressed, a triangle is activated and so on. This graphical interface allows the teacher to shift between different shapes and set the modality task that has to be performed, i.e. sketching, coloring in or cutting operations. Figure 2(d) shows the screen that has been used during the test of the robotic and multimodal system. While the people without skills are the end-users of this technology, it is possible to consider a more person-centered approach.

Multimodal assistance through haptics

In its simplest form, a point-based haptic device (like the Phantom Desktop device) is a transmission between three DC brushed motors with encoders and the human hand. The x, y and z coordinates of the users' fingertip are tracked with the encoders, and the motors control the x, y and z forces exerted upon the user. The Haptic Guidance Device concept has been realized in a series of virtual and physical prototypes to enable evaluation of its potential for improving 2D operations (sketching, coloring in and cutting tasks). In order to enable the 2D operations by the user, several configurations have been analyzed. This section describes the concept in which the tool for sketching and coloring in can be replaced with the wire-cutting tool.

Figure 3 provides several CAD views of the MGS from the users' side. The user is sitting in front of the haptic guidance device in a comfortable way, and then by handling the stylus (4) tries to follow the sketch (8) from the physical template (3) in order to perform the 2D tasks. These tasks are driven by the operator's movement and assisted by the Magnetic Geometry Effect (MGE). The MGE constraint is linked to the external surface (9) of the virtual object that has been previously created by using a CAD software and the stylus haptic point (7). When this option is activated, a spring force tries to pull the sphere of the stylus (7) of the haptic device towards the virtual surface (9) of the 3D model (10). In fact, this effect is used to assist the users' hand movements. In the cutting modality, while user follows the 2D template (8) using the MGS, the wire tool, which is carried out by the 2DOF mechanism (2) cuts the polystyrene foam (5). The polystyrene foam is an interchangeable element. Note that in the intersection between the external surface (9) and the stylus haptic point (7), there is a working plane (11). In fact, this working plane is a physical constraint created by the 2DOF mechanism linked to the Phantom device (1). Figure 3 also shows in detail the sound strategy adopted.

This configuration allows 2 haptic degrees of freedom through the Phantom device. The ''Z'' displacement in the Phantom device is blocked by using the link element (4) through the haptic guidance device and the Phantom. In fact, Figure 3(d) shows the way in which the element (4) is linked to the ground and the Phantom device in order to allow the planar motion of the point ''A'' that is fixed to the stylus pen.

Design of the 2DOF mechanism

The various stages involved in the design of the 2DOF mechanism that is linked to the Phantom device have been intended to:

(1) Define the topology of the kinematic chain underlying the mechanical links and elements;
(2) Define the geometric dimensions of the various links and components defining the main frame, as required to reach different 2D virtual templates and to satisfy the haptic workspace and weight requirements;
(3) Define the structural dimensioning of the various links, components and joints, as needed to meet static load requirements, where load includes both forces and moments under the most demanding operation condition, e.g. the user's pressure by hand while using the stylus of the Phantom device.

Noting that topology selection and geometric dimensioning are strictly coupled with the kinematic design process, we first begin with an examination of the haptic workspace provided by the Phantom Device and its kinematic properties.

We then review in detail both the geometric dimensions so as to satisfy the 2D virtual sketches that the haptic guidance device is able to reach and the length of the links.

We then performed a structural analysis of the links, components and joints so as to meet both static and dynamic load requirements.

The prototype

The main structure used for the MGS has been designed taking into account some important considerations related to the use of sheet metal and aluminum components that implies: low inertia, light weight parts and low friction. Regarding the static and dynamic modeling, the links and components are considered to be rigid. However, the haptic guidance device is not a rigid structure. To provide this stiffness, the links have been designed as beams or shell structures. In order to assemble the different components some considerations have been made: the selection of revolute joints and its stiffness or resistance to all undesired motion, the shafts diameter, clearances and tolerances and mounting configurations of the components. Also, the mounting arrangement of the main structure has been designed to accommodate manufacturing tolerances. Figure 4(a) shows the physical prototype of the multimodal system as

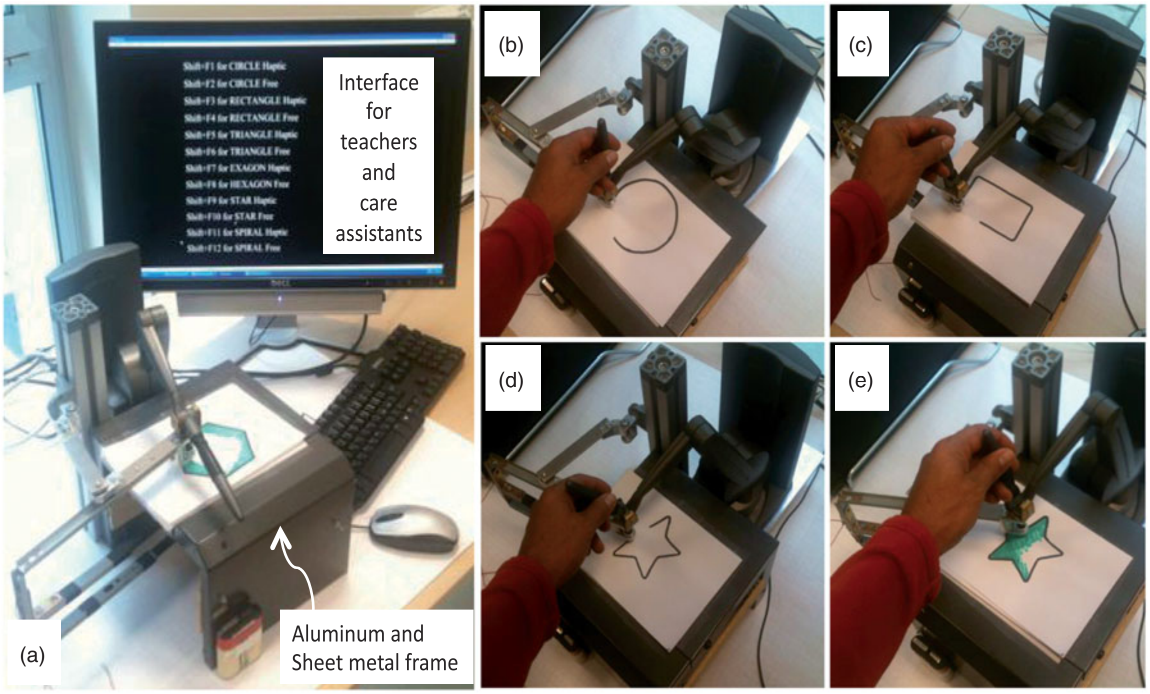


Figure 4. The prototype of the MGS.

described in previous sections. The aluminum and sheet metal frame is linked to the Phantom device. Figure 4(b)–(d) show the user while sketching a shape by using the stylus. In fact, the stylus is linked to a pen, which is an interchangeable element, allowing the user to easily change from one color to another. Figure 4(e) shows the user while filling the inner surface of the shape. Noting the position of the 4 volts DC battery that is connected to the cutting wire tool through the red wires.

The battery is required in order to safely produce the necessary heat to cut the polystyrene. The safety is really an important constraint that has been addressed in order to prevent any unsecured condition by the user.

We decided to use a DC low voltage instead of an AC high voltage for producing the heat. In fact, 4 volts are enough for heating the wire used as cutting tool.

Evaluation of the multimodal guidance device

This section presents the methodology for the evaluation of the MGS, with the aim of reach rigorous, valid, reliable, systematic, useful and practical conclusions about the designed device. In our research we have been interested in two main aspects. The first was to evaluate the haptic guidance device with selected target users; the second was to re-design the device and provide guidelines for the design of future devices using the evaluation results. For this reason, the methodology is based on an iterative and continuous process of data collection, analysis and interpretation. In order to obtain more information about the various aspects of the device functioning, the methodology plans to test the device with three different kinds of population. The contribution of each population to the development of the device will be expressed in the three experiments performed. It is important to notice that this iterative process requires a continuous relationship with the people without skills and their teachers. This consideration demands a conceptual and methodological shift from doing research on how people use the haptic guidance system towards doing research with the people who use the MGS. In other words, it means that the users of the MGS are not the objects of the research, but are active participants who can influence the design of the haptic guidance system and can contribute in making decisions about its usability, effectiveness and practical use.

The methodology consists of three experiments. The aim of each experiment is related to provide qualitative and quantitative results, depending on the task performed and on the sample of the participants. Validating the accuracy of the device for both users and teachers also requires an appropriate collection of data and some interviews or questionnaires appropriately designed to gauge the teachers' views.

The methodology should allow capturing appropriate data that can provide answers to the research questions, such data being both valid and reliable as far as possible. In order to accomplish this objective we structured the testing session in three phases, each of them composed by an experiment on a different population of interest, depending on the aim of the phase. First, we consider able-bodied people in order to validate the accuracy of the system (Experiment 1). Then, we have considered people without skills and their teachers as subject of the research; this means thinking of them as active subject not only in using the haptic guidance device as instructed, but also active in reformulating its use and adapting it to their needs (Experiment 2 and Experiment 3).

(a) Experiment 1: Validation of accuracy with able-bodied people

This phase aims to validate the accuracy of the system in quantitative way. Several tests have been performed with able-bodied people in order to detect the precision of the haptic guidance device while performing drawing tasks as for example sketching and coloring in, but also, while performing the foam cutting task.

(b) Experiment 2: Preliminary test with people without skills

This phase aims to monitor and collect data on the evolution of users' changes and of the device development. It seeks to capture how people without skills and their teachers' cope with the new technology, what changes the new technology demands, as well as most importantly giving indications of the impact of the technology and requirements for its redesign and improvement. At the end of experiment 2 we have drawn some preliminary conclusions taking into account the results of comparing the sketching data obtained by using the device with and without the haptic support. On the basis of the results obtained in this experiment, we have planned to revise the tests to perform with people without skills.

(c) Experiment 3: Structured tests performed by inexperienced people

On the basis of the lessons learned in experiment 2, the evaluation tests have been revised so as to adopt only those that have proven to be effective and successful. At the end of experiment 3, the data collected have been compared in order to highlight the advantages of using the haptic guidance system.

Experiment 1: Validating the system

We carried out several preliminary tests in order to verify the users improvements while performing 2D operations by using the haptic guidance device. The accuracy on the 2D operations has been measured using as input the Phantom device. This operation has been performed by the stylus of the Phantom device using the DeviceLog command provided by the H3D API platform. The tracked sample rate was 25 Hz.

The task

On each experiment, the task consisted in tracing a circle with and without haptic guidance. The difference between the circle that the participants had to trace and the traced circles have been described by using the equation of a circle in terms of difference of radius in each point of the circles.

Sketching task by able-bodied people

In this task, a 2D printed sketch (a circle with 100 mm of radius) has been provided with the same coordinate system as that used by the 2D haptic sketch. Ten able-bodied participants from the Politecnico di Milano participated in this study. The group consisted of 7 male and 3 female participants between the ages of 20 and 33. All the participants reported normal sense of

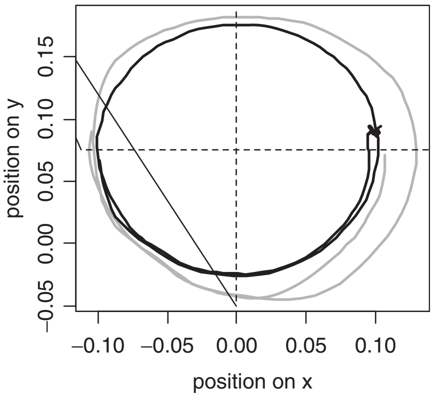


Figure 5. Sketching task performed by able-bodied people.

touch and vision, and all of them were right-handed. First, we requested that participants complete a free sketch by means of using the device without the haptic support, then the same sketch was drawn by enabling the 2D haptic sketch as a guide path.

Figure 5 shows the resulting path tracked by the user's sketching operation in which the haptic feedback is not enabled (gray tracked curve). The same sketch operation with the haptic feedback enabled has been performed (black tracked curve); we can observe a strong difference in the accuracy of the operation.

The most evident advantage provided by the 2D haptic sketches is the accuracy as can be seen from Figure 6. The time has been normalized in order to render the plot.

Figure 6 reports only the results of one of the testers (S1), however, a plot of the rating data showing the mean and the standard deviation for each participant is shown in Figure 7 both with and without haptic feedback, respectively. This plot reports the error (mm) measured on the complete group of participants.

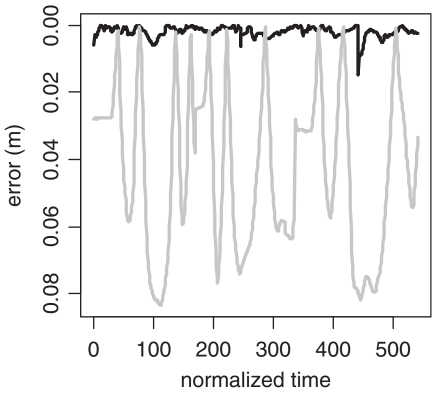


Figure 6. Error reported while sketching (one healthy user).

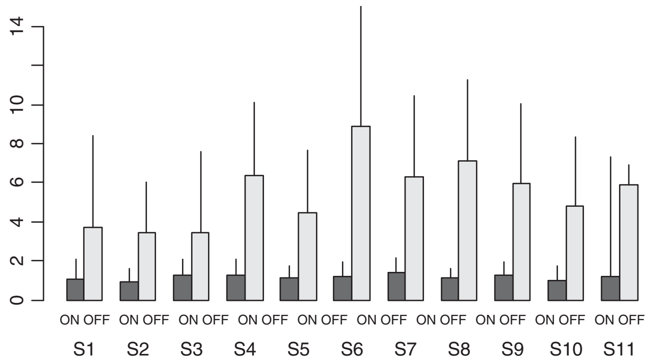


Figure 7. Error reported by able-bodied people.

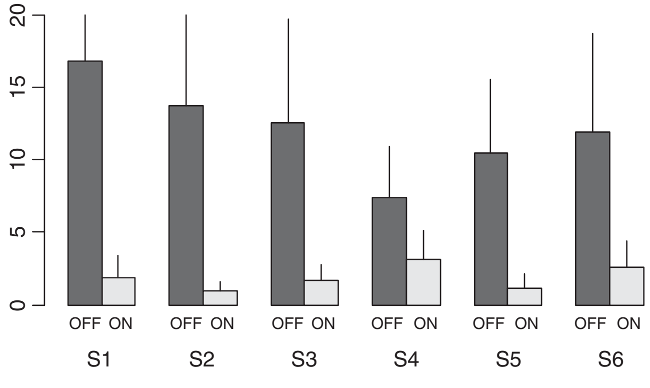


Figure 8. Error reported by people without skills.

In fact, without the haptic guidance the error average is 5.92 mm (median 6.13 mm), while by using the haptic guidance the error average is 1.15 mm (median 1.16 mm). Wilcoxon rank sum test showed a significant difference between the error with and without haptic guidance ($p < 0.05$).

Experiment 2: Validating the system by people without skills

For the validation process we also experimented our system with our first population of people without skills. Even if this pre-test is not compulsory and can sometimes be avoided, it is useful to have a prior experiment with a flexible experimental paradigm on the population of interest. For this test we took data from 6 participants (4 males) aged 18 to 40 years. All participants had developmental disabilities. Also in this experiment a brief familiarization with our system was provided to the participants, and all participants were asked to perform a task that involved a combination of visual and haptic functions in order to design a circle with 100 mm of radius. In order to systematically assess the contribution of the haptic guidance we computed the error between the radius of the circles as previously described and reported on Figure 8.

Results based in the Wilcoxon rank sum test showed that the error significantly decreases ($p < 0.05$) when participants were guided.

Without the haptic feedback, the error average was 12.7 mm (median 12.64 mm) and with the haptic feedback the error drastically decreased up to 1.9 mm (median 2.47 mm).

Experiment 3: impact of the sound on people without skills performance

In this section, we present an approach that uses sound to communicate position and velocity. The sound feedback of the MGD gives the possibility to play sounds while the users interact with the system. We used the sound in order to provide information to the PWD according to the type of task performed. Important goals on the design of the sound feedback include the need to ensure that the information is effectively communicated to the user, the need to minimize the time it takes for the user to learn how to interpret the sounds and also, the selection of sound that does not annoy or irritate the user [13]. In our work we tested two different sound feedbacks acting as metaphor on two different aspect of the task: position of the pen during the tracing and velocity of execution of the task. In particular, as mentioned earlier, we consider only a 2-D cross-sectional slice of the virtual object (on the haptic working plane). The two sound feedbacks have been chosen in order to provide the following information:

(a) Metaphoric sound A, if the stylus pen is not correctly located on the shape. This sound is a kind of warning alarm.
(b) Metaphoric sound B, is played when the velocity of the stylus pen is higher than an specific value. Also in this case, the sound is rendered as a warning alarm.

Note that the sound A was a direct feedback the correctness of the participant's performance, whereas the sound B had been set to force the participant to slowly move the pen along the border of the shape. This choice is motivated by the evidence that a slower action in drawing and copying task is usually associated with a better performance, and then the second sound may be considered as an indirect feedback about subject performance.

Testing session

The user test has been performed involving 11participants (4 males) aged 18 to 40 years. All participants had developmental disabilities. We performed a first testing session lasting eight

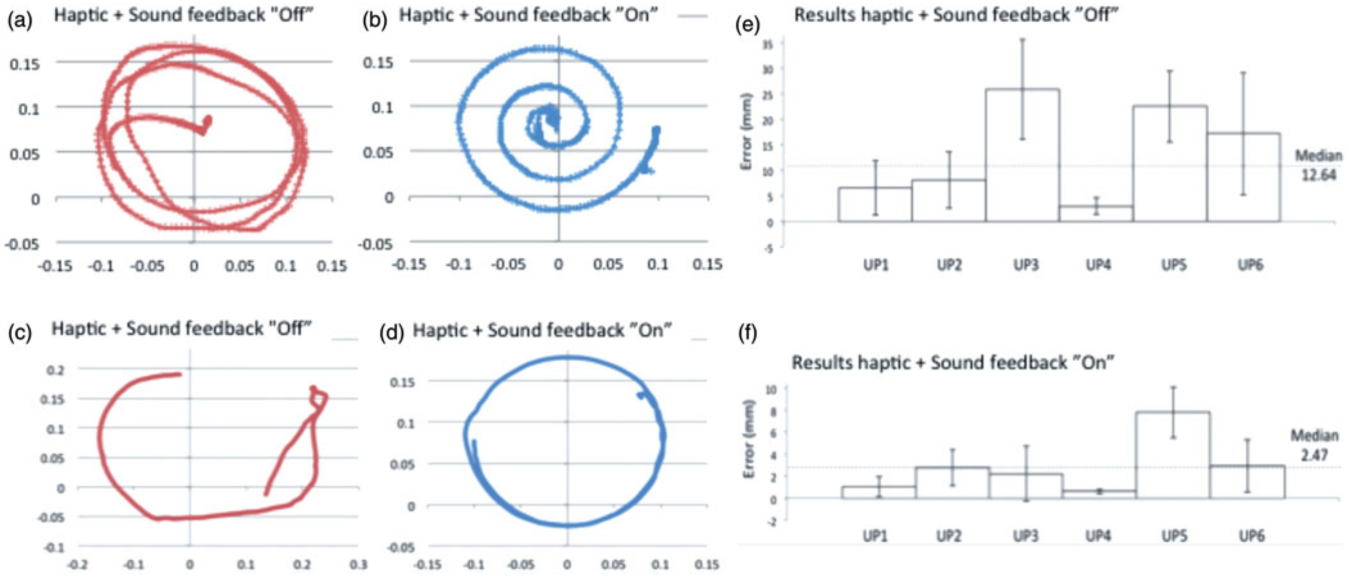


Figure 9. Error amount for a typical subject without feedback (gray line) and with audio-haptic feedback.

repetitions on these participants, utilizing the device without giving any acoustic feedback. In this experiment a brief familiarization has been offered to the participants and it has been asked them to perform a task that involved a combination of visual and haptic functions in order to trace out a circle with 100 mm of radius. Figure 9 shows the tracked motion with (right) and without (left) haptic guidance while sketching the circle. In order to systematically assess the contribution of the haptic guidance we computed the error between the radius of the circles as previously described. Results confirmed, as in the previous experiments, that the error significantly decreased (Wilcoxon rank sum test $p < 0.05$) when participants were guided.

In order to assess the impact of the acoustic feedback on the subject ability in performing the task, we repeated the experiment enabling sounds A and B on the multimodal device. During the first session 3 of the 11 participants have not been able to accomplish the task. Their behavior indicated that the sound had a strong influence on their attention. In fact, these participants moved the pencil in order to hear the device sound, rather than to copy the circle. In order to reverse this counterproductive effect we reverted the conditions in which the sound was played. In particular:

(a) Metaphoric sound A, stopped to play if the stylus pen was not located directly on the shape.
(b) Metaphoric sound B, stopped to play if the velocity of the stylus pen was higher than an specific value.

As results, the efficacy of the device has been restored. Wilcoxon test showed a significant difference between errors during the free tracing of the circle and the trace with haptic and acoustic feedback ($p < 0.05$ for each subject, data achieved on eight repetition). At last we compared the participants errors obtained in the only haptic condition to those obtained in the acoustic-haptic condition. Unfortunately, statistic tests did not show any difference between the two conditions ($p = 0.87$). This is probably due by the easiness of the task. In our opinion participants did not need additional help than the haptic feedback in an easy task like copy a circle. Anyway, based on the results with the first sound configuration, and based on the qualitative feedback, the importance of the sound feedback on the subject performance is clear. Further experiments will be addressed in understanding how to implement the correct acoustic feedback to improve the subject performance, involving more complex tasks.

Further device uses

Coloring in internal surfaces

In the coloring in task we request to fill the internal surface of the butterfly sketch as can be seen in Figure 10(a). Figure 10(b) shows the coloring in operation performed by the user without the haptic feedback, in fact, the 2D haptic sketch has been disabled. Figure 10(c) shows the coloring in operation with the haptic feedback enabled.

Also in this operation is evident the advantage of using the 2D haptic sketches as a virtual guide for assisting the user's hand movement while coloring in a region.

Cutting shapes

To start the cutting trial, we asked participants to use the haptic guidance device with the wire as cutting tool. For instance, we positioned the wire-cutting tool in the start point and then the user moved the stylus of the device according with the 2D haptic sketch geometry. Figure 11 shows several products in which the haptic guidance device has been used as a cutting tool.

Discussion

The results of our study showed that the haptic guidance device helps people during sketching, coloring in and cutting operations by means of using haptic technology. However, we cannot compare the accuracy for example of the cutting components made with the haptic guidance device with the ones produced with traditional machining processes or with CNC technology in which the components can be made with a high degree of accuracy. Nevertheless, when the cutting modality of the haptic guidance device is used, it is also possible to design and create 2D sketches in which high precision is not required. In fact, all the products made with the haptic guidance device are hand-made assisted ones.

Conclusion

The Multimodal Guidance Device assists people without skills in the assessment and training of hand movements. We explored user performance while using the haptic point-based approach. The results of our study showed that the MGS helps people

Figure 10. Coloring in operation.

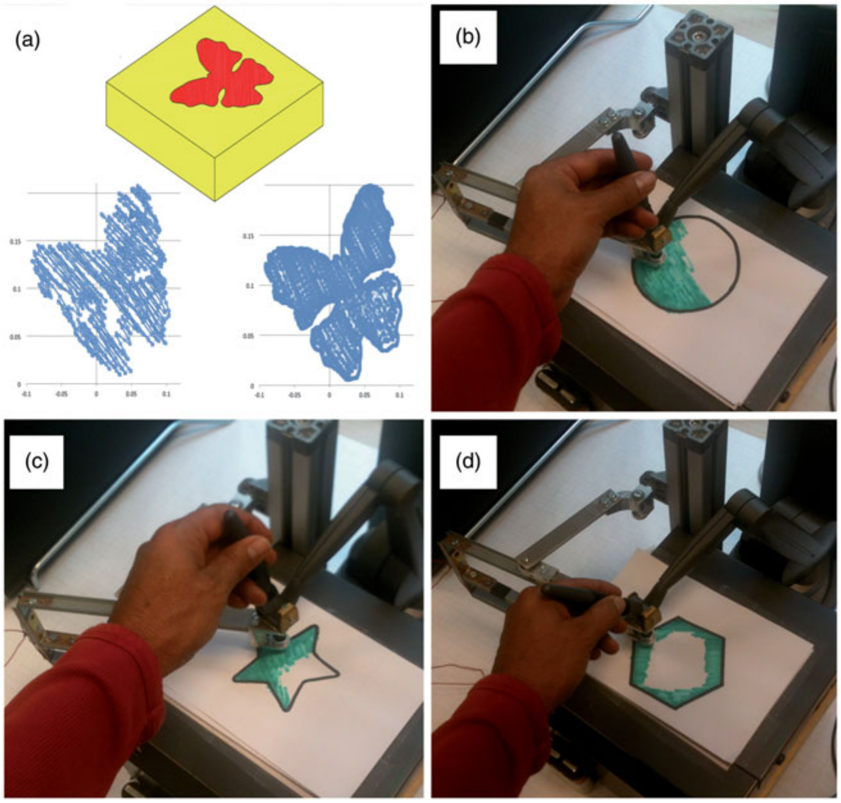


Figure 11. Examples of wire cutting products.

during manual tasks by means of using haptic and sound technology.

The opportunity to create a haptic system that would make a real difference in the lives of persons with developmental disabilities appeared to be a highly motivating factor.

We are currently performing an evaluation with people without skills in order to measure their learning improvements in 2D operations skills. Results show that the effect of using the haptic cutting system increases the accuracy in the tasks operations.

We can assume that the system leads to the satisfaction of the following objectives:

- The force feedback enhances the interaction between the user and the physical template.
- The sound feedback is an and additional channel information used to perform the 2D tasks according to the correct velocity.

Future work

Future research on the device and its application might be able to point out the role of acoustic feedback in the drawing and cutting tasks. Moreover, we aim to introduce the device in the learning environment to check how it fits in with existing practices of teaching and learning manual activities.

Furthermore, a series of tests are currently being performed to also assess the impact of the device on the subject's ability to learn in a short or longer-term.

Finally, we are also working to improve the performance of the cutting haptic device by increasing the working volume.

Acknowledgments

The authors would like to thank Emanuele Fedeli, instructor at Laboratorio Artimedia (Calolziocorte, Italy); Sarah Leveraro, Barbara Spreafico and Barbara Pandiani, instructors and teachers at Casa Dei Ragazzi Treves De Sanctis O.N.L.U.S., and Centro Diurno Disabili Di Barzanò for their support in the preliminary evaluation of the haptic guidance device and for giving us the opportunity to test the system.

Declaration of interest

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

References

1. Ahlstrom D. Modeling and improving selection in cascading pull-down menus using Fitts' Law, the steering law and force fields. In: Proceedings of the SIGCHI conference on Human factors in computing systems, CHI '05, ACM, 2005:61–70.
2. Teo C, Burdet E, Lim H. A robotic teacher of chinese handwriting. In: Proceedings of the 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems 2002.
3. Liu A, Tendick F, Cleary K, Kaufmann C. A survey of surgical simulation: applications, technology, and education. Presence: Teleoper. Virtual Environ, 12 Dec, 2003:599–614.
4. Palsbo SE, Marr D, Streng T, et al. Towards a modified consumer haptic device for robotic-assisted fine-motor repetitive motion training. Disabil Rehabil: Assistive Technol 2011;6:546–51.
5. PHANToM device, SenSable Technologies Inc., Available from: http://www.sensable.com [last accessed 4 March 2013].
6. Mensvoort KV, Hermes DJ, Montfort MV. Usability of optically simulated haptic feedback. Int J Hum Comput Stud 2008;66: 438–51.
7. Rodgers M, Mandryk R, Inkpen K. Smart sticky widgets: pseudo-haptic enhancements for multi-monitor displays. In: Butz A, Fisher B, Krüger A, Olivier P, eds. Vol. 4073 of Lecture Notes in Computer Science. Berlin/Heidelberg: Springer; 2006, pp. 194–205.
8. Blank R, Heizer W, von Voss H. Externally guided control of static grip forces by visual feedback age and task effects in 3-6 old children and adults. Neurosc Lett 1999;271:41–4.
9. Kurillo G, Gregorič M, Goljar N, Bajd T. Grip force tracking system for assessment and rehabilitation of hand function. Technol Health Care 2005;13:137–49.
10. Charlton JL, Ihsen E, Lavelle BM. Control of manual skills in children with down syndrome. In: Weeks D, Chua R, Elliot DJ, eds. Perceptual-motor behavior in Down syndrome. Champaign (IL): Human Kinetics; 2000:25–48.
11. Jansson G, Ostrom M. The effects of co-location of visual and haptic space on judgments of form. EuroHaptics 2004:516–19.
12. Wall S, Paynter K, Shillito A, et al. The effect of haptic feedback and stereo graphics in a 3d target acquisition task. In: Proceedings of Eurohaptics 2002, University of Edinburgh, 8–10 July, N/A, 2002:23–29.
13. Begault DR. 3-D sound for virtual reality and multimedia. New York: AP professional; 1994.