A Multimodal Interface Device for Online Board Games Designed for Sight-Impaired People

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***Abstract*—Online games between remote opponents playing over computer networks are becoming a common activity of everyday life. However, computer interfaces for board games are usually based on the visual channel. For example, they require players to check their moves on a video display and interact by using pointing devices such as a mouse. Hence, they are not suitable for visually impaired people. The present paper discusses a multipurpose system that allows especially blind and deafblind people playing chess or other board games over a network, therefore reducing their disability barrier. We describe and benchmark a prototype of a special interactive haptic device for online gaming providing a dual tactile feedback. The novel interface of this proposed device is able to guarantee not only a better game experience for everyone but also an improved quality of life for sight-impaired people.**

***Index Terms*—Blindness, board games, deafblindness, haptic device, multimodal feedback.**

I. Introduction

GAME playing over the Internet has significantly changed the approach to board games such as chess. At first available only for rich communities, in recent years it has become a familiar concept for most of the people, and online tournaments and championships are now widespread. Also, the playing style has been influenced by the availability of online huge databases with openings and endgames. Today, Internet board games and especially chess represent a great opportunity for players, trainers, and professionals, besides having a strong impact on the younger generation of players, which can learn and play the game at their own convenience.

The interest in chess among blind people has increased in many countries over the years, and chess tournaments are held by dedicated organizations such as the International Braille Chess Association (IBCA) [1]. However, blind people have no dedicated online chess association, likely due to the difficulty in using common interfaces for online games. As a result, although IBCA is recognized as a part of the International Blind Sportsmen Association (IBSA), teams from IBCA have taken part in chess Olympiads only four times since 1994. In real life, blind people play chess or any other similar game thanks to special boards, where cells have distinctive patterns, therefore, they can be recognized by touching them [2]. Pieces are designed to be easily distinguishable at touch, and in addition, they can be steadily stuck in the center of a square to avoid the alteration in game configuration on touching them. Such a checker and chess set costs about $30 [3]. Additional improvements [4] involve magnets under the pieces and a rigid metallic sheet beneath the playing surface, which enhances the stability of the game configuration when a blind person "reads" the board by touching it. However, these special boards are not easy to interface with computer systems.

Conversely, the available software interfaces for remote games are designed only for sighted people, since players interact using a mouse and a standard screen. Therefore, blind people should be provided with some extra tool providing a nonvisual representation of the board. One possibility is to replace the screen with a tactile interface controlled by an electromechanical device, providing information about the actual configuration of the board and being capable to refresh it at each turn. Even though this could be implemented with an *ad hoc* electromechanical board, such a solution would not be efficient in terms of cost and complexity.

The approach, we adopt in this paper uses instead a more natural interaction model, in which information about the game configuration is provided exactly as in face-to-face situations. Our main contribution is the design of a multipurpose device, especially targeted at blind and deafblind people, providing players with multimodal feedback. The proposed device is able to give a nonsequential representation of information; thus, visually impaired players can freely navigate over the squares and learn about the game configuration as though they were touching the real pieces. Several Braille-based devices could be suitable in order to implement this solution, e.g., computer accessories enabling visually impaired users to read Braille characters on a screen [5]. Especially, tactile communication systems [6] can be implemented as low-cost input/output peripherals, shaped like a computer mouse, consisting of a haptic device, where a Braille display and an optical sensor are embedded together with a tactile information system. Input is acquired by sensing the finger pressure with a grid of 64 electrodes, whereas output uses low-voltage electrical current as a stimulus; mechanoreceptors' axons within nervous cells underneath the fingertip are excited with anodic or cathodic current, so as to generate different sensations on the user's skin.

Nonetheless, many challenges need to be solved to achieve practical usability. First of all, the sensibility to electrical current, which the device uses as stimulus, is different among individuals; even for the same person, skin impedance is time-varying and strongly depends on the environment. Moreover, such

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devices offer haptic feedback, but do not provide any spatial information about the cursor position. Hence, the user does not receive feedback when navigating over the screen apart from the movement of his/her hand. As a result, visually impaired users are able to recognize the direction in which they are driving the device, but they are not aware of the exact location of the pointer on the screen. To solve such problems, our implementation adds the missing spatial feedback, properly elicited through a further tactile channel. In the following, we describe the implementation details of our prototype. Eventually, the device realizes a bidirectional feedback, and is therefore able to provide the users with spatial awareness of the board configuration, while at the same time making the acquisition homogeneous for multiple users. We believe that filling the gap in the availability of online board games for visually impaired people represents an original and significant contribution towards the reduction of disability barriers.

The rest of this paper is organized as follows. In Section II, we discuss the need for tactile bidirectional feedback, and in Section III, we describe how this is introduced by our novel approach, detailing physical, control, and communication issues. In Section IV, we describe how we validated and quantitatively evaluated our approach via experiments. Finally, we conclude in Section V.

II. Choice of Feedback Strategies

The sense of sight is the major perceptual channel for the human being. However, visually impaired people need to replace it with other sensory channels, such as touch or hearing. The tactile channel is more robust in noisy environments; besides, it is the only viable possibility for those blind people who are also deaf or have hearing impairments. We remark that, from a general viewpoint, haptic feedback is known to improve human–computer interaction significantly. Several studies [7] show that visual feedback can be improved, and in certain cases even replaced, by tactile stimuli. At the same time, also audio feedback is known [8] to further improve the performance from haptic devices. For all these reasons, our proposed system can combine all the three channels, i.e., simultaneously provide visual, audio, and tactile feedback in a multimodal fashion. In the following, we will focus on the main original feature of our proposal, i.e., the introduction of a bidirectional tactile feedback. However, this solution is straightforward to integrate with audio feedback as well. We also point out that our system guarantees an improved usability for any kind of user, including sighted people.

Note that, we do not provide just a plain vibrotactile feedback. Such a feature is already available in many devices, which, however, simply use it to convey warnings or other binary notifications. The main original contribution of our system is to enable a concrete spatial perception for visually impaired people. As players know, figuring out the spatial disposition of pieces over the board significantly improves the game experience. To this end, we designed a bimodal tactile interaction and a more expressive feedback environment based on several information types. Continuous control operations, such as the navigation over the screen, can be executed seamlessly exploiting tactile feedback providing immediate spatial information; thanks to vibrotactile actuators, they constantly feel the trajectory of their movement and may adjust it at any time.

A further challenge was to create a proper feedback for discrete control operations (i.e., read texts or symbols on-screen), without affecting or interfering with the information about continuous control. Most solutions employed to this end split information over two channels, i.e., to combine haptic continuous feedback and sounds associated with discrete events [8]. Yet, such an approach does not guarantee privacy or concentration during game and is prone to errors due to ambient acoustic noise. Finally, it is not suitable for deafblind players.

Our proposal implements instead a bimodal tactile feedback through haptic channel splitting. The rationale behind our idea is as follows. First of all, we observe that even blind people with hearing impairments are usually able to read Braille displays, thus we propose to use piezoelectric dynamic Braille cells [9]. This technology mimics existing Braille chessboards [2], where tactile information allows recognizing checkers and pieces. Finally, we observe that there are different kinds of mechanoreceptors responding to multiple levels of pressure [10]. Rapidly adapting receptors react to an immediate stimulus, while slowly adapting receptors respond to continuously applied pressure. Therefore, according to the type of operation (continuous or discrete control) the system provides a different tactile feedback using vibrotactile actuators (continuous pressure) or a refreshing Braille tactile actuator (discrete stimulus). Also, this bimodal haptic feedback allows the parallel use of different actuators for event notifications (as is needed, e.g., when the application alerts the user and requires him to read a text which is not in the cursor position). As a consequence, we rely on the sense of touch as a common information source for several types of noncollapsing messages. Board games require conveying different types of information such as game status (the configuration of the board and the status of the game), time (elapsed and remaining), events, and system responses, which need to be adequately represented.

III. System Design

As our system is multipurpose, many applications are possible. However, we think that board games are an interesting use case, since they have a wide variety of interaction situations, and are also entertaining, which makes the voluntary evaluation easier by test subjects. Chess is a good choice, since it is one of the most articulated board games; as it requires the player to spend considerable effort in decision-making, and accurate perception and cognition of the game configuration are required.

In this sense, there is a gap between sighted and blind players, which require an alternative to the visual channel to gather and organize information during the game. In traditional board games, a blind player can touch the chessboard and feel the placement of pieces. For this reason, our system is designed to have an emulation of this behavior usable in an online context, so that the blind player can manipulate a tangible virtual representation of the chessboard. In this way, the accessibility

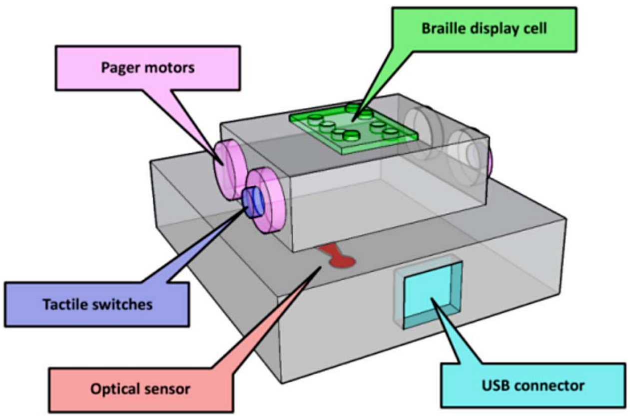

Fig. 1. Design of the hardware prototype.

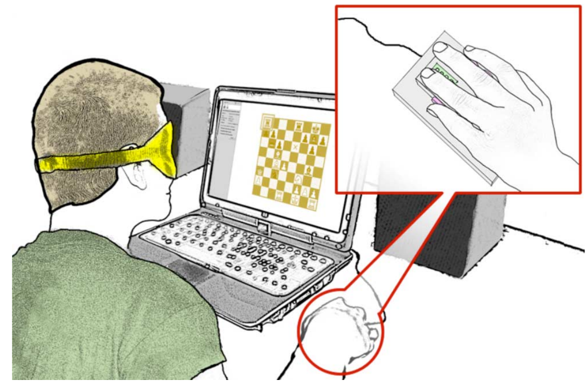

Fig. 2. Device utilization.

of online gaming would be possible also for visually impaired people. In the following, we describe in detail hardware and software aspects of our proposal.

A. Hardware Design

The peripheral is designed to achieve high modularity and component independency. We adopt a layered structure, especially conceived for interactive devices. It consists of three independent components, namely the *physical*, the *control*, and the *communication* layer. The physical layer exchanges input/output data, directly interacts with the user, and passes information to the control layer. This provides a feedback to the physical layer and interfaces the network data exchange coming from the communication layer. This last layer is connected to a network server for dataflow exchange. In our prototype, all layers are assembled onto one board. The exterior of the device contains the physical layer. The hardware enclosure of the system consists of a small plastic case, so as to achieve a mouse-like shape that can be driven with one hand. Total size of the device is 12 mm (L) × 8 cm (W) × 8 cm (H). An optical sensor is located underneath the device. Two pairs of pager motors are located on both left and right sides to be in contact with the distal and the intermediate phalanges of the thumb, and the middle finger of the user. The tactile switches are located above the pager motors in the distal area, one on the left and the other on right, therefore, they can be easily pressed. The Braille cell is placed on the top of the peripheral and it is in contact with the distal phalanx of the second finger. The control board is located within the case, on the same board as the communication layer. The peripheral can be physically connected to a computer via a USB/serial port or can have a wireless connection (e.g., Bluetooth, ZigBee).

1) Physical Layer: The physical layer (see Fig. 1) is actually split into two separate peripherals for input and output. The input device consists of two different sensors, the board navigator, and the move selector. The output subsystem also consists of two components, the former providing feedback about the navigation over the board and the latter giving information about the content of squares. This layer contains the circuitry connecting the electronic components (sensors and actuators) for input/output exchange.

The board navigator is an optic-mechanical component capable to detect 2-D motion over the underlying plane. It acquires continuous movements over a flat surface and determines the distance between starting and ending points within a certain time window. This element can be implemented with a LED (or an infrared laser diode) and photodiodes. The diode illuminates the surface; changes are acquired, processed, and translated into movements on the two axes using off-the-shelf algorithms. This kind of sensor is surface-independent, i.e., it does not require a dedicated chessboard, in the same way as computer mice do not need a special mouse pad. The board navigator enables the control layer to know the exact coordinates of the device as (x, y) pairs, with respect to a reference position. Then, a microcontroller translates the information provided by the board navigator into the movement of a pointer over the computer screen, analogous to a mouse cursor. We employed a common 3-mm red LED and a standard CMOS sensor. The light bounces from the surface onto the CMOS, which acquires images to be processed with a DSP algorithm. In this way, it is possible to detect movement patterns, evaluate the corresponding coordinates, and update the cursor position on screen.

The move selector basically consists of two buttons, located in a position, which is easily reachable by fingers (preferably the thumb and the middle finger) when the device is held. The purpose is to issue commands as sequences of button-click actions. In the case of chess, this determines the moves. To acquire impulses, we employed low-profile (0.5 cm × 0.5 cm × 0.3 cm) tactile switches, which provide excellent tactile feedback (sensitive release), high reliability (their mean actuation force is 1.35 ± 0.50 N), and a long life (200 000–100 0000 expected cycles). Moreover, they are very cheap (about $0.20 each). Extra buttons can easily be added to provide other control capabilities or more input dimensions. The resulting device utilization is visually represented in Fig. 2.

The provider of navigation feedback is realized with four pager motors, acting as transducers to convert electrical signals into tactile stimuli in the form of vibrations. These components are akin to those embedded into mobile phones and pagers to provide vibrations, in addition to or in replacement of the ringing tone. Pager motors generate high amplitude of oscillating forces; they are compact, cost-effective, highly customizable,

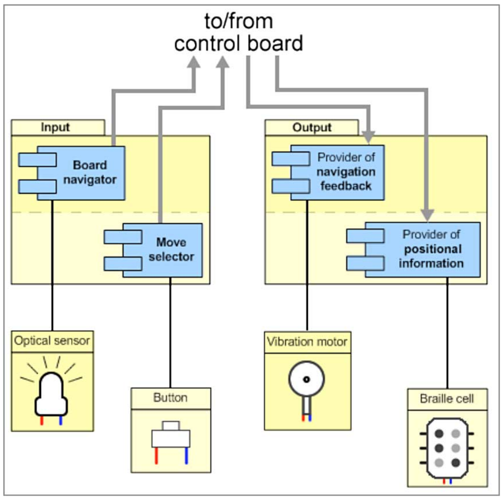

Fig. 3. Overview of the physical layer architecture.

and suitable for small electronic appliances. Moreover, they are available in several packages, including the shaftless type. These units are a slight variant of the traditional vibrator motor, since they are fully enclosed, without external moving parts. Our implementation includes four motors whose operating voltage ranges from 2.5 to 3.8 V, with maximum speed of 12 000 rpm and current absorption of 85 mA. We used miniaturized (1.0 × 1.0 × 0.3 cm), and lightweight (1 g each) button-style shaftless motors, with a 2 ms response time. Several alternative small vibrating devices are available in the market.

The architecture of the physical layer, detailed in Fig. 3, contains several elements that deserve more emphasis. The provider of positional information consists of one lightweight and small size Braille display cell. While the user navigates over the board, information about the value of each position is provided in real-time using a piezoelectric display unit, which is capable of representing a refreshable Braille character. Piezoelectric cells have been developed for visually impaired people to allow them to read by touching a display with a line made of several cells. Each piezoelectric unit consists of eight actuators arranged in a rectangular array of 4 × 2 dots. The height of each point with respect to the cell surface is controlled by a bimorph, which is stimulated with electrical signals to bend up or down. As a result, the actuators extend (rise) or contract (fall) and they create the Braille characters. Several countries defined different standards for the horizontal and vertical distance between the dots, diameter of points, elevation of the piezoelectric actuator with respect to the surface of the cell, and other characteristics. We implemented an International Building Standard [11] compliant cell (2.5 mm for horizontal and vertical dot-to-dot distance, with a dot diameter of 1.5–1.6 mm and a dot height ranging from 0.6 to 0.9 mm). Also, this kind of components relies on direct electrical control; it provides fast feedback to the user (the Braille cell has an activation time of ~0.01 ms and a settling time of ~0.15 s). The stiffness of the actuators is approximately 5 N. In terms of information representation, as the piezoelectric Braille cell has eight dots, it is possible to encode up to $2^8 =$ 256 symbols, which is sufficiently high for any board or even card game.

2) Control Layer: This layer contains the processing unit (microprocessor), which manages the device operation and translates physical stimuli into logical messages for the game. When the user navigates over the board or selects a starting and an ending position, the microcontroller gets sequences of electrical inputs from the sensors located at the physical layer, converts them into logical messages, and sends to the communication layer. When data are received from the upper layer, the control layer converts them into stimuli and triggers the actuators, by firing pager motors or displaying a symbol on the Braille cell. Both control and communication layers are implemented in an open source multiplatform hardware prototype equipped with USB connection, the Arduino Nano control board [12], which includes a 16 MHz ATmega168 microcontroller with 1 kB SRAM, 14 digital input/output pins and 6 analog inputs. It supports pulsewidth modulation (PWM) on 6 output pins. It has small form factor (1.85 mm × 4.31 mm) and operates at 5 V, powered by the on-board mini-USB connector. The firmware is programmed within the processing environment in a C-like or Java-like language.

The board navigator acquires input about the spatial location of the device (if it is not in sleep state) at a high frequency (1000 Hz). The microcontroller processes the sampled CMOS signals incoming on pins from 23 to 26, and it converts them into pairs of bytes representing the actual coordinates. Then, it sends them to the communication layer by raising a pos(x, y) event with a frequency equal to the sampling rate. Also, each button-click raises a different event that is sent to the device driver through the communication layer. Sequences of clicks generate command configurations, which are interpreted by the device driver. For instance, the user selects the starting position of a move by clicking button A (start-square selection button) and then drops the piece on the final position by clicking button B (end-square selection button) or clicks button A again to choose another (nonempty) starting position. By clicking both buttons at the same time, the board navigator is reset to the default position (center of the chessboard).

The microcontroller receives and executes commands from the communication layer through serial communication. Each incoming message consists of 2 B, representing the command code and a parameter, respectively. Thus, up to 255 commands and parameter values can be used. Examples of commands include: 1) provide navigation feedback; 2) provide positional information; or 3) generate arbitrary time delays. Thus, navigation feedback commands trigger vibrations of one or more motors with a given intensity, which is sent to the physical layer as a digitally generated analogue 8-bit PWM output (on pins 3, 5, 6, and 9). Voltage amplitudes are represented by integers with four possible levels (zero, low, medium, high). As we have 4 motors, this information can be encoded with a byte (2 bits per each motor). A positional information command changes instead the Braille cell configuration by raising or lowering one or more piezoelectric actuators. Its parameter represents the state of each of the 8 dots (0 for low, 1 for high) starting from the first row and the first column, so that 256 cell configurations

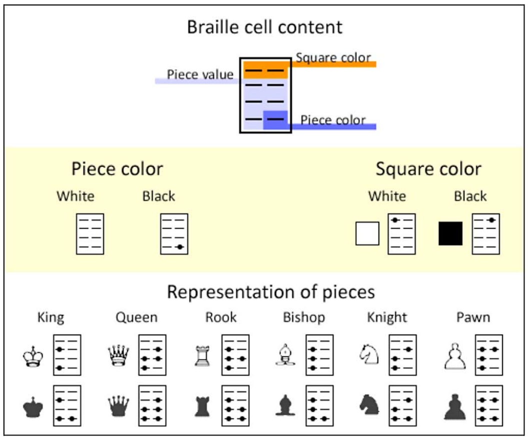

Fig. 4. Braille coding for chess playing.

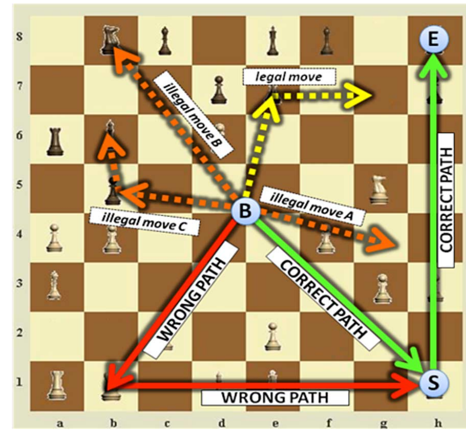

Fig. 5. Moves and paths of the experimental task.

can be displayed. Fig. 4 reports an example for chess, using the international Braille code.

3) Communication Layer: This module consists of the electronic components allowing the device to transfer data and interact with the network. Several wired or wireless connection types can be supported. The control system natively implemented a standard serial RS-232 port. We added USB support, which also provides power supply within the connection cable. Several wireless solutions, e.g., Bluetooth or ZigBee, can be used with an additional battery.

Due to our modular approach, the network interface does not require any special change to the device. This implies that other games than chess can be played with the same device, by simply changing the client/server model implemented in the local communication protocol. The game software of the system acts as a client requesting service to the device driver of the hardware where the application is run. We enabled their processes to establish a local user datagram protocol (UDP) connection and exchange streams of data and share messages between the client (the game software) and the server (the device driver). In this way, a single peripheral can interact with several software applications. Even though the client/server model introduces a higher-level abstraction, a serial communication is realized between the driver and the peripheral; it occurs without any handshaking procedure and it has the following settings: the baud rate of the transmission is set to 9600, the number of data bits encoding a character is set to 8, there is no parity bit and one stop bit is used.

B. Software Design

Blind and deafblind people usually interact with technologies based on text interfaces such as screen readers; linear output devices are known to be tedious because they do not allow the users to freely navigate over two axes. Instead of a text-based implementation, the software component of the system has a GUI typical of standard windows-icons-menu-pointing (WIMP) device applications. It supports different directions of movement over the board and obtains a mouse-like interaction during the game. The software architecture ensures (using the power of polymorphism) to handle different types of players (sighted, blind, and deafblind). As a result, players can be differently handled and the feedback of the system after each movement is diverse. For instance, a blind player is informed about whether he/she is moving over the board or outside of the border; while the sighted player receives a feedback only for move validity and the game status after his/her move. However, whenever a player starts a new game, the feedback is automatically set to fit any particular need, being transparent to the user.

In our proposed system, we considered three levels of users: novices, intermediate players, and professionals, mirroring the hierarchy of official chess schools or academies. For each user type and player level, the system dynamically allows to set feedback according to the specific needs of the player. Novices can access a tutorial (see Fig. 5), explaining the rules of chess where they have a constant feedback about their errors. This is a key social aspect, e.g., to reduce the barriers experienced by blind children in learning chess, as they encounter difficulties in attending classes together with sighted children. At the same time, this also may improve the self-esteem and confidence of the blind child, who can experience the game training similar to sighted players. Intermediate and professional blind players can instead play directly the real game. Intermediate players are prompted for confirmation, in order to improve their confidence with the game and/or the device, whereas, professional players are assumed to master both of them and do not receive any additional help in this sense.

IV. System Evaluation

We conducted a controlled experiment focusing on the board navigator, the move selector, and the provider of navigation feedback. Our aim was to study whether the users are able to perceive the actual configuration of the environment, and/or at the same time detect if any manipulation occurs. The total duration of the experiment was about 40 min, including the training and the experimental phases. At the end, we submitted a questionnaire to measure the users' satisfaction and their subjective evaluation of game experience. The questionnaire required five additional minutes to be filled in.

TABLE I
PERFORMANCE EVALUATION RESULTS

Subject	Age	G	C	SF (%)	WTM (ms)	MA (%)	PA (%)
S1	25	M	Y	94	7135	96.60	82.03
S2	15	F	N	86	7338	94.92	77.58
S3	54	F	Y	84	8272	96.12	82.74
S4	61	M	Y	72	8960	95.91	85.10
S5	23	F	Y	84	7592	94.80	82.15
S6	26	M	Y	94	6985	97.91	85.55
S7	30	M	N	84	7516	95.61	76.57
S8	33	M	N	86	8479	97.81	83.94
S9	42	F	Y	82	7642	95.80	74.21
S10	18	M	Y	88	6828	95.99	77.41
S11	21	F	Y	90	6472	97.03	82.19
S12	35	F	Y	90	8129	96.62	80.06
S13	38	M	N	84	8809	94.74	75.26
S14	43	M	Y	88	8757	95.55	75.57

G = gender, C = chess player, SF = average success-to-failure ratio, WTM = average weighted time required to complete the move, MA = average move attention, PA = average path accuracy.

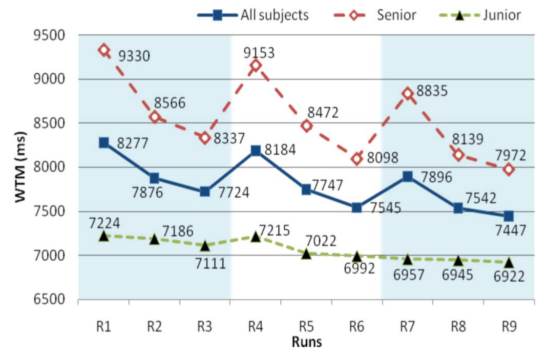

Fig. 6. Impact of training factor on the WTM.

A. Participants

We recruited 14 participants, 6 females (S2, S3, S5, S9, S11, and S12) and 8 males, as reported in Table I. Their ages ranged from 15 to 61 years, with an average of $\sim$33. All have normal sight, hearing and tactile sensitivity, but during the experiment they were blindfolded to simulate the loss of the visual channel. All subjects use computers on a daily basis and were considered novice for what concerns the player level, as they never used the device before; 10 of them are chess players, the others (S2, S7, S8, and S13) just had vague knowledge of the game. All subjects collaborated on a voluntary basis.

B. Experimental Task

The experiment consisted of executing simple tasks issued through vocal commands, a possible tutorial procedure to train novices. During the experiment, the proposed device was the only user interface with the virtual chessboard. Each volunteer was asked to perform 45 tasks, organized into 3 groups of 3 runs each, so that each run consisted of 5 subsequent task executions (called "trials" in the following). The inter-trial and the inter-run intervals were 2 s and 30 s long, respectively. After each group of runs subjects rested for 2 min.

The task required at each trial was to move a piece from a square to another, similar to what shown in Fig. 5. To simulate a game-play case, the chessboard was occupied by other pieces, as it would be during real games. At the beginning of each trial the cursor position was set at the center of the board (B) and the move was announced, e.g., "move the white rook from H1 to H8." Users had to check whether the move was legal, i.e., there actually was a white rook in H1, and the move to H8 was allowed by chess rules, i.e., in this specific example, the intermediate squares are free (as the chess rook does not "jump") and H8 is either free or occupied by a black piece. If some condition was violated, users had to discard the move by clicking both buttons. Otherwise, they had to move the device until reaching the starting square S (H1 in the example), pick the said piece by pressing the left button, drag it to the end square E (in the example, H8), and drop it by using the right button.

The chessboard configuration was refreshed at the beginning of each trial. Each trial was randomly generated, so that legal and illegal moves were equally probable. In both cases, color and value of the piece, as well as start/end squares, were also chosen at random. A trial timeout was set with respect to the distance between the start and the end location, i.e., 1 s per square plus a fixed amount of 5 s.

C. Performance Evaluation

As the main variables, we analyzed the success-to-failure (SF) ratio, the weighted time required to complete the move (WTM), the path accuracy (PA) and the move attention (MA). SF is the average percentage of correct moves. WTM is the interval between the beginning of the trial and the accomplishment of the move, weighted on the move length (normalized on a five square move). PA is the reciprocal of the deviation from the minimum length of the path. MA is the percentage of illegal moves correctly detected and discarded.

D. Results

The SF, having an average of $86.14 \pm 5.52\%$ indicates that all subjects were generally able to understand the task and accomplish it before the timeout. Our findings suggest that experience in chess playing gives a slight advantage; the average SFs of chess-players and nonchess-players are 86.6% and 85.0%, respectively. Subjects were generally able to recognize when they were asked to perform an illegal move, and they reported it quickly. As a result, their achieved MA is always higher than 94%, with an average MA of $96.1 \pm 1.01\%$. This means that they were able to recognize the content of the squares and that tactile feedback about navigational information does not prevent the user to focus on cognitive tasks. Users were less precise in moving the piece across the chessboard, resulting in lower PA performance with an average value of $80.03 \pm 3.86\%$. However, path accuracy was determined with respect to an ideal, straight path, which players rarely follow in real chess.

Subject spent an average of 7780 ms to complete a five squares long move. Actually, this value is subject to a training effect. While there is no difference in PA, MA, and SF between the runs, there is a decreasing trend in the WTM, as can be seen in Fig. 6. The results reported in this figure are averaged on the same run; in this manner, even though the tasks are randomly generated, and therefore generally different, the effect of these differences is removed. The evolution of the curve between the trials of the same group of runs indicates that users become more responsive as long as they are exposed to the system. We found an interesting dependence of the WTM on the age of the participants. To better highlight it, we classify the participants in two age groups, denoted as "junior" and "senior" (age $\leq$30 and $>$30, respectively). As reported in Fig. 6, the WTM is around 20% higher for senior subjects. The difference between groups might be due to the shorter learning curve of junior subjects, which may have better sensitivity and are likely familiar with multi-sensorial devices. The curves reported in Fig. 6 also show some spikes for runs 1, 4, and 7; in practice, they are present only in the curve of senior subjects, while they are almost negligible for junior subjects. A reasonable explanation is that, when the experiment is resumed after a pause, some time is needed (especially by senior users) to become again familiar with the device.

Although questionnaires reported that the task was challenging, data show no attenuation of performances due to habituation to prolonged tactile stimuli, or fatigue in using the device.

V. Conclusion

We developed a practical and low-cost system architecture, which enables remote board game playing over a network for visually impaired people. We also discussed several feasibility issues showing that our solution is cost-effective and easy to implement. Moreover, it can be combined with other feedback techniques and is simple to use even for nonimpaired people.

The most expensive part is the piezoelectric Braille cell, which can be found as a stand-alone device with cost of about $35. Other components are relatively cheaper and easy to find in the market. Actually, sensors and actuators (except the Braille cell) can be gathered from spare hardware; our prototype was built from leftovers of nonfunctioning peripherals (a computer mouse and mobile phones). The Braille cell constitutes the only significant expense, making the overall cost of the same order of magnitude for a mechanic chessboard with neither electronic nor network support. The overall cost can be estimated below $80 for a unique complete device, which is cost-effective compared to other solutions, e.g., a chessboard made of 64 Braille displays, and offers the advantage of being portable for nonstandard checkers, e.g., shogi, which is played on a 9 $\times$ 9 chessboard.

Further improvements might concern power saving techniques to reduce energy consumption, especially for the battery-powered wireless model. Similar to a computer mouse, our device can include a standby-mode during which the laser or the LED is blinking instead of continuously active. Moreover, as board games are turn based, several power saving conditions can be introduced in order to save energy, for instance, sleeping states during the opponent's move. Finally, our intent is to propose the system to associations assisting blind people, such as IBCA, and experiment its usage by blind professional chess players, e.g., against sighted opponents.

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A Multimodal Interface Device for Online Board Games Designed for Sight-Impaired People

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***Abstract*—Online games between remote opponents playing over computer networks are becoming a common activity of everyday life. However, computer interfaces for board games are usually based on the visual channel. For example, they require players to check their moves on a video display and interact by using pointing devices such as a mouse. Hence, they are not suitable for visually impaired people. The present paper discusses a multipurpose system that allows especially blind and deafblind people playing chess or other board games over a network, therefore reducing their disability barrier. We describe and benchmark a prototype of a special interactive haptic device for online gaming providing a dual tactile feedback. The novel interface of this proposed device is able to guarantee not only a better game experience for everyone but also an improved quality of life for sight-impaired people.**

***Index Terms*—Blindness, board games, deafblindness, haptic device, multimodal feedback.**

I. Introduction

GAME playing over the Internet has significantly changed the approach to board games such as chess. At first available only for rich communities, in recent years it has become a familiar concept for most of the people, and online tournaments and championships are now widespread. Also, the playing style has been influenced by the availability of online huge databases with openings and endgames. Today, Internet board games and especially chess represent a great opportunity for players, trainers, and professionals, besides having a strong impact on the younger generation of players, which can learn and play the game at their own convenience.

The interest in chess among blind people has increased in many countries over the years, and chess tournaments are held by dedicated organizations such as the International Braille Chess Association (IBCA) [1]. However, blind people have no dedicated online chess association, likely due to the difficulty in using common interfaces for online games. As a result, although IBCA is recognized as a part of the International Blind Sportsmen Association (IBSA), teams from IBCA have taken part in chess Olympiads only four times since 1994. In real life, blind people play chess or any other similar game thanks to special boards, where cells have distinctive patterns, therefore, they can be recognized by touching them [2]. Pieces are designed to be easily distinguishable at touch, and in addition, they can be steadily stuck in the center of a square to avoid the alteration in game configuration on touching them. Such a checker and chess set costs about $30 [3]. Additional improvements [4] involve magnets under the pieces and a rigid metallic sheet beneath the playing surface, which enhances the stability of the game configuration when a blind person "reads" the board by touching it. However, these special boards are not easy to interface with computer systems.

Conversely, the available software interfaces for remote games are designed only for sighted people, since players interact using a mouse and a standard screen. Therefore, blind people should be provided with some extra tool providing a nonvisual representation of the board. One possibility is to replace the screen with a tactile interface controlled by an electromechanical device, providing information about the actual configuration of the board and being capable to refresh it at each turn. Even though this could be implemented with an *ad hoc* electromechanical board, such a solution would not be efficient in terms of cost and complexity.

The approach, we adopt in this paper uses instead a more natural interaction model, in which information about the game configuration is provided exactly as in face-to-face situations. Our main contribution is the design of a multipurpose device, especially targeted at blind and deafblind people, providing players with multimodal feedback. The proposed device is able to give a nonsequential representation of information; thus, visually impaired players can freely navigate over the squares and learn about the game configuration as though they were touching the real pieces. Several Braille-based devices could be suitable in order to implement this solution, e.g., computer accessories enabling visually impaired users to read Braille characters on a screen [5]. Especially, tactile communication systems [6] can be implemented as low-cost input/output peripherals, shaped like a computer mouse, consisting of a haptic device, where a Braille display and an optical sensor are embedded together with a tactile information system. Input is acquired by sensing the finger pressure with a grid of 64 electrodes, whereas output uses low-voltage electrical current as a stimulus; mechanoreceptors' axons within nervous cells underneath the fingertip are excited with anodic or cathodic current, so as to generate different sensations on the user's skin.

Nonetheless, many challenges need to be solved to achieve practical usability. First of all, the sensibility to electrical current, which the device uses as stimulus, is different among individuals; even for the same person, skin impedance is time-varying and strongly depends on the environment. Moreover, such

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devices offer haptic feedback, but do not provide any spatial information about the cursor position. Hence, the user does not receive feedback when navigating over the screen apart from the movement of his/her hand. As a result, visually impaired users are able to recognize the direction in which they are driving the device, but they are not aware of the exact location of the pointer on the screen. To solve such problems, our implementation adds the missing spatial feedback, properly elicited through a further tactile channel. In the following, we describe the implementation details of our prototype. Eventually, the device realizes a bidirectional feedback, and is therefore able to provide the users with spatial awareness of the board configuration, while at the same time making the acquisition homogeneous for multiple users. We believe that filling the gap in the availability of online board games for visually impaired people represents an original and significant contribution towards the reduction of disability barriers.

The rest of this paper is organized as follows. In Section II, we discuss the need for tactile bidirectional feedback, and in Section III, we describe how this is introduced by our novel approach, detailing physical, control, and communication issues. In Section IV, we describe how we validated and quantitatively evaluated our approach via experiments. Finally, we conclude in Section V.

II. Choice of Feedback Strategies

The sense of sight is the major perceptual channel for the human being. However, visually impaired people need to replace it with other sensory channels, such as touch or hearing. The tactile channel is more robust in noisy environments; besides, it is the only viable possibility for those blind people who are also deaf or have hearing impairments. We remark that, from a general viewpoint, haptic feedback is known to improve human–computer interaction significantly. Several studies [7] show that visual feedback can be improved, and in certain cases even replaced, by tactile stimuli. At the same time, also audio feedback is known [8] to further improve the performance from haptic devices. For all these reasons, our proposed system can combine all the three channels, i.e., simultaneously provide visual, audio, and tactile feedback in a multimodal fashion. In the following, we will focus on the main original feature of our proposal, i.e., the introduction of a bidirectional tactile feedback. However, this solution is straightforward to integrate with audio feedback as well. We also point out that our system guarantees an improved usability for any kind of user, including sighted people.

Note that, we do not provide just a plain vibrotactile feedback. Such a feature is already available in many devices, which, however, simply use it to convey warnings or other binary notifications. The main original contribution of our system is to enable a concrete spatial perception for visually impaired people. As players know, figuring out the spatial disposition of pieces over the board significantly improves the game experience. To this end, we designed a bimodal tactile interaction and a more expressive feedback environment based on several information types. Continuous control operations, such as the navigation over the screen, can be executed seamlessly exploiting tactile feedback providing immediate spatial information; thanks to vibrotactile actuators, they constantly feel the trajectory of their movement and may adjust it at any time.

A further challenge was to create a proper feedback for discrete control operations (i.e., read texts or symbols on-screen), without affecting or interfering with the information about continuous control. Most solutions employed to this end split information over two channels, i.e., to combine haptic continuous feedback and sounds associated with discrete events [8]. Yet, such an approach does not guarantee privacy or concentration during game and is prone to errors due to ambient acoustic noise. Finally, it is not suitable for deafblind players.

Our proposal implements instead a bimodal tactile feedback through haptic channel splitting. The rationale behind our idea is as follows. First of all, we observe that even blind people with hearing impairments are usually able to read Braille displays, thus we propose to use piezoelectric dynamic Braille cells [9]. This technology mimics existing Braille chessboards [2], where tactile information allows recognizing checkers and pieces. Finally, we observe that there are different kinds of mechanoreceptors responding to multiple levels of pressure [10]. Rapidly adapting receptors react to an immediate stimulus, while slowly adapting receptors respond to continuously applied pressure. Therefore, according to the type of operation (continuous or discrete control) the system provides a different tactile feedback using vibrotactile actuators (continuous pressure) or a refreshing Braille tactile actuator (discrete stimulus). Also, this bimodal haptic feedback allows the parallel use of different actuators for event notifications (as is needed, e.g., when the application alerts the user and requires him to read a text which is not in the cursor position). As a consequence, we rely on the sense of touch as a common information source for several types of noncollapsing messages. Board games require conveying different types of information such as game status (the configuration of the board and the status of the game), time (elapsed and remaining), events, and system responses, which need to be adequately represented.

III. System Design

As our system is multipurpose, many applications are possible. However, we think that board games are an interesting use case, since they have a wide variety of interaction situations, and are also entertaining, which makes the voluntary evaluation easier by test subjects. Chess is a good choice, since it is one of the most articulated board games; as it requires the player to spend considerable effort in decision-making, and accurate perception and cognition of the game configuration are required.

In this sense, there is a gap between sighted and blind players, which require an alternative to the visual channel to gather and organize information during the game. In traditional board games, a blind player can touch the chessboard and feel the placement of pieces. For this reason, our system is designed to have an emulation of this behavior usable in an online context, so that the blind player can manipulate a tangible virtual representation of the chessboard. In this way, the accessibility

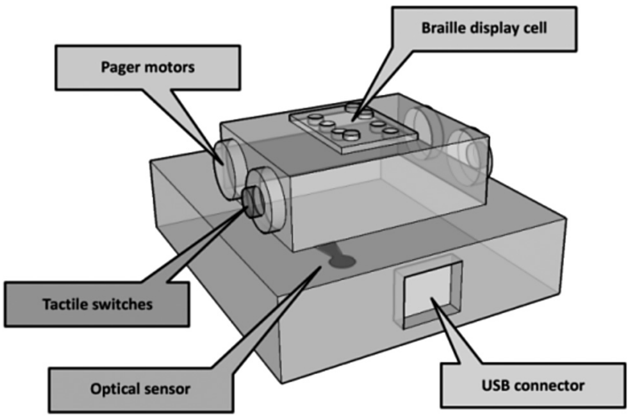

Fig. 1. Design of the hardware prototype.

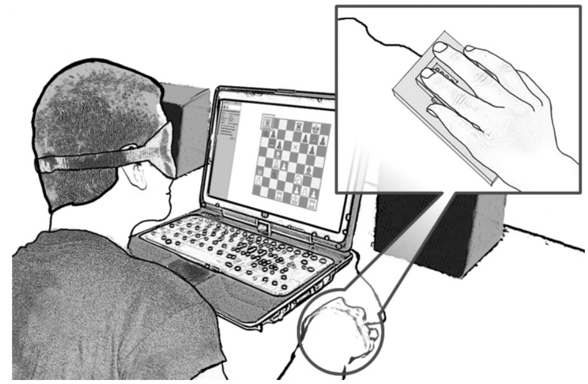

Fig. 2. Device utilization.

of online gaming would be possible also for visually impaired people. In the following, we describe in detail hardware and software aspects of our proposal.

A. *Hardware Design*

The peripheral is designed to achieve high modularity and component independency. We adopt a layered structure, especially conceived for interactive devices. It consists of three independent components, namely the *physical*, the *control*, and the *communication* layer. The physical layer exchanges input/output data, directly interacts with the user, and passes information to the control layer. This provides a feedback to the physical layer and interfaces the network data exchange coming from the communication layer. This last layer is connected to a network server for dataflow exchange. In our prototype, all layers are assembled onto one board. The exterior of the device contains the physical layer. The hardware enclosure of the system consists of a small plastic case, so as to achieve a mouse-like shape that can be driven with one hand. Total size of the device is 12 mm (L) × 8 cm (W) × 8 cm (H). An optical sensor is located underneath the device. Two pairs of pager motors are located on both left and right sides to be in contact with the distal and the intermediate phalanges of the thumb, and the middle finger of the user. The tactile switches are located above the pager motors in the distal area, one on the left and the other on right, therefore, they can be easily pressed. The Braille cell is placed on the top of the peripheral and it is in contact with the distal phalanx of the second finger. The control board is located within the case, on the same board as the communication layer. The peripheral can be physically connected to a computer via a USB/serial port or can have a wireless connection (e.g., Bluetooth, ZigBee).

1) Physical Layer: The physical layer (see Fig. 1) is actually split into two separate peripherals for input and output. The input device consists of two different sensors, the board navigator, and the move selector. The output subsystem also consists of two components, the former providing feedback about the navigation over the board and the latter giving information about the content of squares. This layer contains the circuitry connecting the electronic components (sensors and actuators) for input/output exchange.

The board navigator is an optic-mechanical component capable to detect 2-D motion over the underlying plane. It acquires continuous movements over a flat surface and determines the distance between starting and ending points within a certain time window. This element can be implemented with a LED (or an infrared laser diode) and photodiodes. The diode illuminates the surface; changes are acquired, processed, and translated into movements on the two axes using off-the-shelf algorithms. This kind of sensor is surface-independent, i.e., it does not require a dedicated chessboard, in the same way as computer mice do not need a special mouse pad. The board navigator enables the control layer to know the exact coordinates of the device as (x, y) pairs, with respect to a reference position. Then, a microcontroller translates the information provided by the board navigator into the movement of a pointer over the computer screen, analogous to a mouse cursor. We employed a common 3-mm red LED and a standard CMOS sensor. The light bounces from the surface onto the CMOS, which acquires images to be processed with a DSP algorithm. In this way, it is possible to detect movement patterns, evaluate the corresponding coordinates, and update the cursor position on screen.

The move selector basically consists of two buttons, located in a position, which is easily reachable by fingers (preferably the thumb and the middle finger) when the device is held. The purpose is to issue commands as sequences of button-click actions. In the case of chess, this determines the moves. To acquire impulses, we employed low-profile (0.5 cm × 0.5 cm × 0.3 cm) tactile switches, which provide excellent tactile feedback (sensitive release), high reliability (their mean actuation force is 1.35 ± 0.50 N), and a long life (200 000–100 0000 expected cycles). Moreover, they are very cheap (about $0.20 each). Extra buttons can easily be added to provide other control capabilities or more input dimensions. The resulting device utilization is visually represented in Fig. 2.

The provider of navigation feedback is realized with four pager motors, acting as transducers to convert electrical signals into tactile stimuli in the form of vibrations. These components are akin to those embedded into mobile phones and pagers to provide vibrations, in addition to or in replacement of the ringing tone. Pager motors generate high amplitude of oscillating forces; they are compact, cost-effective, highly customizable,

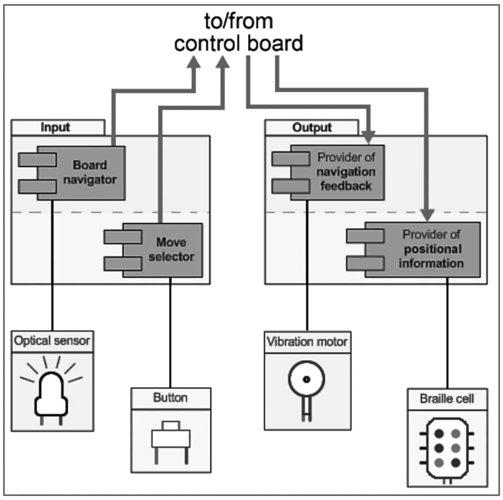

Fig. 3. Overview of the physical layer architecture.

and suitable for small electronic appliances. Moreover, they are available in several packages, including the shaftless type. These units are a slight variant of the traditional vibrator motor, since they are fully enclosed, without external moving parts. Our implementation includes four motors whose operating voltage ranges from 2.5 to 3.8 V, with maximum speed of 12 000 rpm and current absorption of 85 mA. We used miniaturized (1.0 × 1.0 × 0.3 cm), and lightweight (1 g each) button-style shaftless motors, with a 2 ms response time. Several alternative small vibrating devices are available in the market.

The architecture of the physical layer, detailed in Fig. 3, contains several elements that deserve more emphasis. The provider of positional information consists of one lightweight and small size Braille display cell. While the user navigates over the board, information about the value of each position is provided in real-time using a piezoelectric display unit, which is capable of representing a refreshable Braille character. Piezoelectric cells have been developed for visually impaired people to allow them to read by touching a display with a line made of several cells. Each piezoelectric unit consists of eight actuators arranged in a rectangular array of 4 × 2 dots. The height of each point with respect to the cell surface is controlled by a bimorph, which is stimulated with electrical signals to bend up or down. As a result, the actuators extend (rise) or contract (fall) and they create the Braille characters. Several countries defined different standards for the horizontal and vertical distance between the dots, diameter of points, elevation of the piezoelectric actuator with respect to the surface of the cell, and other characteristics. We implemented an International Building Standard [11] compliant cell (2.5 mm for horizontal and vertical dot-to-dot distance, with a dot diameter of 1.5–1.6 mm and a dot height ranging from 0.6 to 0.9 mm). Also, this kind of components relies on direct electrical control; it provides fast feedback to the user (the Braille cell has an activation time of ∼0.01 ms and a settling time of ∼0.15 s). The stiffness of the actuators is approximately 5 N. In terms of information representation, as the piezoelectric Braille cell has eight dots, it is possible to encode up to $2^8 =$ 256 symbols, which is sufficiently high for any board or even card game.

2) Control Layer: This layer contains the processing unit (microprocessor), which manages the device operation and translates physical stimuli into logical messages for the game. When the user navigates over the board or selects a starting and an ending position, the microcontroller gets sequences of electrical inputs from the sensors located at the physical layer, converts them into logical messages, and sends to the communication layer. When data are received from the upper layer, the control layer converts them into stimuli and triggers the actuators, by firing pager motors or displaying a symbol on the Braille cell. Both control and communication layers are implemented in an open source multiplatform hardware prototype equipped with USB connection, the Arduino Nano control board [12], which includes a 16 MHz ATmega168 microcontroller with 1 kB SRAM, 14 digital input/output pins and 6 analog inputs. It supports pulsewidth modulation (PWM) on 6 output pins. It has small form factor (1.85 mm × 4.31 mm) and operates at 5 V, powered by the on-board mini-USB connector. The firmware is programmed within the processing environment in a C-like or Java-like language.

The board navigator acquires input about the spatial location of the device (if it is not in sleep state) at a high frequency (1000 Hz). The microcontroller processes the sampled CMOS signals incoming on pins from 23 to 26, and it converts them into pairs of bytes representing the actual coordinates. Then, it sends them to the communication layer by raising a pos(x, y) event with a frequency equal to the sampling rate. Also, each button-click raises a different event that is sent to the device driver through the communication layer. Sequences of clicks generate command configurations, which are interpreted by the device driver. For instance, the user selects the starting position of a move by clicking button A (start-square selection button) and then drops the piece on the final position by clicking button B (end-square selection button) or clicks button A again to choose another (nonempty) starting position. By clicking both buttons at the same time, the board navigator is reset to the default position (center of the chessboard).

The microcontroller receives and executes commands from the communication layer through serial communication. Each incoming message consists of 2 B, representing the command code and a parameter, respectively. Thus, up to 255 commands and parameter values can be used. Examples of commands include: 1) provide navigation feedback; 2) provide positional information; or 3) generate arbitrary time delays. Thus, navigation feedback commands trigger vibrations of one or more motors with a given intensity, which is sent to the physical layer as a digitally generated analogue 8-bit PWM output (on pins 3, 5, 6, and 9). Voltage amplitudes are represented by integers with four possible levels (zero, low, medium, high). As we have 4 motors, this information can be encoded with a byte (2 bits per each motor). A positional information command changes instead the Braille cell configuration by raising or lowering one or more piezoelectric actuators. Its parameter represents the state of each of the 8 dots (0 for low, 1 for high) starting from the first row and the first column, so that 256 cell configurations

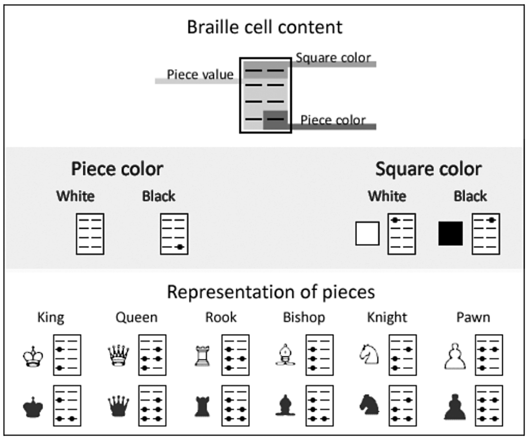

Fig. 4. Braille coding for chess playing.

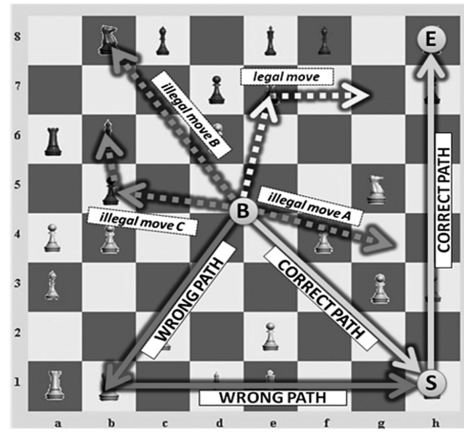

Fig. 5. Moves and paths of the experimental task.

can be displayed. Fig. 4 reports an example for chess, using the international Braille code.

3) Communication Layer: This module consists of the electronic components allowing the device to transfer data and interact with the network. Several wired or wireless connection types can be supported. The control system natively implemented a standard serial RS-232 port. We added USB support, which also provides power supply within the connection cable. Several wireless solutions, e.g., Bluetooth or ZigBee, can be used with an additional battery.

Due to our modular approach, the network interface does not require any special change to the device. This implies that other games than chess can be played with the same device, by simply changing the client/server model implemented in the local communication protocol. The game software of the system acts as a client requesting service to the device driver of the hardware where the application is run. We enabled their processes to establish a local user datagram protocol (UDP) connection and exchange streams of data and share messages between the client (the game software) and the server (the device driver). In this way, a single peripheral can interact with several software applications. Even though the client/server model introduces a higher-level abstraction, a serial communication is realized between the driver and the peripheral; it occurs without any handshaking procedure and it has the following settings: the baud rate of the transmission is set to 9600, the number of data bits encoding a character is set to 8, there is no parity bit and one stop bit is used.

B. Software Design

Blind and deafblind people usually interact with technologies based on text interfaces such as screen readers; linear output devices are known to be tedious because they do not allow the users to freely navigate over two axes. Instead of a text-based implementation, the software component of the system has a GUI typical of standard windows-icons-menu-pointing (WIMP) device applications. It supports different directions of movement over the board and obtains a mouse-like interaction during the game. The software architecture ensures (using the power of polymorphism) to handle different types of players (sighted, blind, and deafblind). As a result, players can be differently handled and the feedback of the system after each movement is diverse. For instance, a blind player is informed about whether he/she is moving over the board or outside of the border; while the sighted player receives a feedback only for move validity and the game status after his/her move. However, whenever a player starts a new game, the feedback is automatically set to fit any particular need, being transparent to the user.

In our proposed system, we considered three levels of users: novices, intermediate players, and professionals, mirroring the hierarchy of official chess schools or academies. For each user type and player level, the system dynamically allows to set feedback according to the specific needs of the player. Novices can access a tutorial (see Fig. 5), explaining the rules of chess where they have a constant feedback about their errors. This is a key social aspect, e.g., to reduce the barriers experienced by blind children in learning chess, as they encounter difficulties in attending classes together with sighted children. At the same time, this also may improve the self-esteem and confidence of the blind child, who can experience the game training similar to sighted players. Intermediate and professional blind players can instead play directly the real game. Intermediate players are prompted for confirmation, in order to improve their confidence with the game and/or the device, whereas, professional players are assumed to master both of them and do not receive any additional help in this sense.

IV. System Evaluation

We conducted a controlled experiment focusing on the board navigator, the move selector, and the provider of navigation feedback. Our aim was to study whether the users are able to perceive the actual configuration of the environment, and/or at the same time detect if any manipulation occurs. The total duration of the experiment was about 40 min, including the training and the experimental phases. At the end, we submitted a questionnaire to measure the users' satisfaction and their subjective evaluation of game experience. The questionnaire required five additional minutes to be filled in.

TABLE I
PERFORMANCE EVALUATION RESULTS

Subject	Age	G	C	SF (%)	WTM (ms)	MA (%)	PA (%)
S1	25	M	Y	94	7135	96.60	82.03
S2	15	F	N	86	7338	94.92	77.58
S3	54	F	Y	84	8272	96.12	82.74
S4	61	M	Y	72	8960	95.91	85.10
S5	23	F	Y	84	7592	94.80	82.15
S6	26	M	Y	94	6985	97.91	85.55
S7	30	M	N	84	7516	95.61	76.57
S8	33	M	N	86	8479	97.81	83.94
S9	42	F	Y	82	7642	95.80	74.21
S10	18	M	Y	88	6828	95.99	77.41
S11	21	F	Y	90	6472	97.03	82.19
S12	35	F	Y	90	8129	96.62	80.06
S13	38	M	N	84	8809	94.74	75.26
S14	43	M	Y	88	8757	95.55	75.57

G = gender, C = chess player, SF = average success-to-failure ratio, WTM = average weighted time required to complete the move, MA = average move attention, PA = average path accuracy.

A. Participants

We recruited 14 participants, 6 females (S2, S3, S5, S9, S11, and S12) and 8 males, as reported in Table I. Their ages ranged from 15 to 61 years, with an average of ∼33. All have normal sight, hearing and tactile sensitivity, but during the experiment they were blindfolded to simulate the loss of the visual channel. All subjects use computers on a daily basis and were considered novice for what concerns the player level, as they never used the device before; 10 of them are chess players, the others (S2, S7, S8, and S13) just had vague knowledge of the game. All subjects collaborated on a voluntary basis.

B. Experimental Task

The experiment consisted of executing simple tasks issued through vocal commands, a possible tutorial procedure to train novices. During the experiment, the proposed device was the only user interface with the virtual chessboard. Each volunteer was asked to perform 45 tasks, organized into 3 groups of 3 runs each, so that each run consisted of 5 subsequent task executions (called "trials" in the following). The inter-trial and the inter-run intervals were 2 s and 30 s long, respectively. After each group of runs subjects rested for 2 min.

The task required at each trial was to move a piece from a square to another, similar to what shown in Fig. 5. To simulate a game-play case, the chessboard was occupied by other pieces, as it would be during real games. At the beginning of each trial the cursor position was set at the center of the board (B) and the move was announced, e.g., "move the white rook from H1 to H8." Users had to check whether the move was legal, i.e., there actually was a white rook in H1, and the move to H8 was allowed by chess rules, i.e., in this specific example, the intermediate squares are free (as the chess rook does not "jump") and H8 is either free or occupied by a black piece. If some condition was violated, users had to discard the move by clicking both buttons. Otherwise, they had to move the device until reaching the starting square S (H1 in the example), pick the said piece by pressing the left button, drag it to the end square E (in the example, H8), and drop it by using the right button.

The chessboard configuration was refreshed at the beginning of each trial. Each trial was randomly generated, so that legal and illegal moves were equally probable. In both cases, color and value of the piece, as well as start/end squares, were also chosen at random. A trial timeout was set with respect to the distance between the start and the end location, i.e., 1 s per square plus a fixed amount of 5 s.

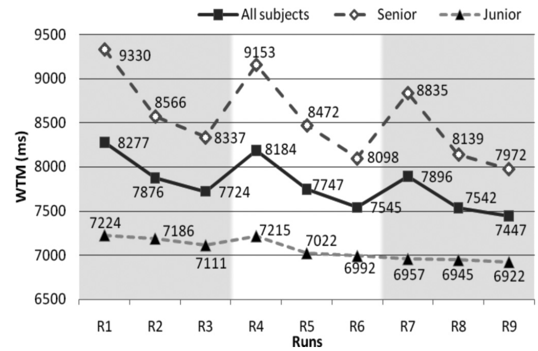

Fig. 6. Impact of training factor on the WTM.

C. Performance Evaluation

As the main variables, we analyzed the success-to-failure (SF) ratio, the weighted time required to complete the move (WTM), the path accuracy (PA) and the move attention (MA). SF is the average percentage of correct moves. WTM is the interval between the beginning of the trial and the accomplishment of the move, weighted on the move length (normalized on a five square move). PA is the reciprocal of the deviation from the minimum length of the path. MA is the percentage of illegal moves correctly detected and discarded.

D. Results

The SF, having an average of $86.14 \pm 5.52\%$ indicates that all subjects were generally able to understand the task and accomplish it before the timeout. Our findings suggest that experience in chess playing gives a slight advantage; the average SFs of chess-players and nonchess-players are 86.6% and 85.0%, respectively. Subjects were generally able to recognize when they were asked to perform an illegal move, and they reported it quickly. As a result, their achieved MA is always higher than 94%, with an average MA of $96.1 \pm 1.01\%$. This means that they were able to recognize the content of the squares and that tactile feedback about navigational information does not prevent the user to focus on cognitive tasks. Users were less precise in moving the piece across the chessboard, resulting in lower PA performance with an average value of $80.03 \pm 3.86\%$. However, path accuracy was determined with respect to an ideal, straight path, which players rarely follow in real chess.

Subject spent an average of 7780 ms to complete a five squares long move. Actually, this value is subject to a training effect. While there is no difference in PA, MA, and SF between the runs, there is a decreasing trend in the WTM, as can be seen in Fig. 6. The results reported in this figure are averaged on the same run; in this manner, even though the tasks are randomly generated, and therefore generally different, the effect of these differences is removed. The evolution of the curve between the trials of the same group of runs indicates that users become more responsive as long as they are exposed to the system. We found an interesting dependence of the WTM on the age of the participants. To better highlight it, we classify the participants in two age groups, denoted as "junior" and "senior" (age $\leq$30 and $>$30, respectively). As reported in Fig. 6, the WTM is around 20% higher for senior subjects. The difference between groups might be due to the shorter learning curve of junior subjects, which may have better sensitivity and are likely familiar with multi-sensorial devices. The curves reported in Fig. 6 also show some spikes for runs 1, 4, and 7; in practice, they are present only in the curve of senior subjects, while they are almost negligible for junior subjects. A reasonable explanation is that, when the experiment is resumed after a pause, some time is needed (especially by senior users) to become again familiar with the device.

Although questionnaires reported that the task was challenging, data show no attenuation of performances due to habituation to prolonged tactile stimuli, or fatigue in using the device.

V. Conclusion

We developed a practical and low-cost system architecture, which enables remote board game playing over a network for visually impaired people. We also discussed several feasibility issues showing that our solution is cost-effective and easy to implement. Moreover, it can be combined with other feedback techniques and is simple to use even for nonimpaired people.

The most expensive part is the piezoelectric Braille cell, which can be found as a stand-alone device with cost of about \$35. Other components are relatively cheaper and easy to find in the market. Actually, sensors and actuators (except the Braille cell) can be gathered from spare hardware; our prototype was built from leftovers of nonfunctioning peripherals (a computer mouse and mobile phones). The Braille cell constitutes the only significant expense, making the overall cost of the same order of magnitude for a mechanic chessboard with neither electronic nor network support. The overall cost can be estimated below \$80 for a unique complete device, which is cost-effective compared to other solutions, e.g., a chessboard made of 64 Braille displays, and offers the advantage of being portable for nonstandard checkers, e.g., shogi, which is played on a 9 $\times$ 9 chessboard.

Further improvements might concern power saving techniques to reduce energy consumption, especially for the battery-powered wireless model. Similar to a computer mouse, our device can include a standby-mode during which the laser or the LED is blinking instead of continuously active. Moreover, as board games are turn based, several power saving conditions can be introduced in order to save energy, for instance, sleeping states during the opponent's move. Finally, our intent is to propose the system to associations assisting blind people, such as IBCA, and experiment its usage by blind professional chess players, e.g., against sighted opponents.

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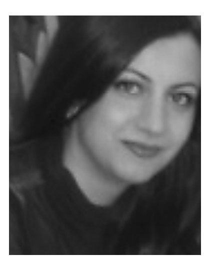

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