Brain-Operated Assistive Devices: the ASPICE Project *

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***Abstract* – The ASPICE project aims at the development of a system which allows the neuromotor disabled persons to improve or recover their mobility (directly or by emulation) and communication within the surrounding environment. The system pivots around a software controller running on a personal computer, which offers to the user a proper interface to communicate through input interfaces matched with the individual's residual abilities. The system uses the user's input to control domotic devices – such as remotely controlled lights, TV sets, etc. – and a Sony AIBO robot.**

At this time, the system is under clinical validation, that will provide assessment through patients' feedback and guidelines for customized system installation.

***Index Terms* – Technologies for Independent Life, Brain-Computer Interfaces, Robotic Navigation, Ambient Intelligence, Severe Motor Impairment.**

I. Introduction

The ultimate objective of medical care or treatment is the recover from the disease, or alternatively the improvement of the clinical symptomatology proper of the disease. In the field of rehabilitation, the main goal is the reduction of the disability provoked by any pathological condition that is the achievement of the maximum independence for a given clinical frame, by means of orthesis and the management of the disability related to the social disadvantage by means of different types of aids.

Recently, the growing evidence for the development of electronic devices capable of ameliorating the possibility to increase the communication and the management of the house-environment has opened new avenues for patients affected by severe movement disorders with preserved cognitive functions. These devices still suffer from limitations due to the necessity of a residual motor ability which might prevent some pathological condition from their use.

It exists today the knowledge to convey a cutting edge technological and scientific result in a way that the largest part of the population can benefit from it.

The project offered the opportunity to integrate into a prototype the technologies described in the three following sections, in order to prove that an application in every day's life is possible, with particular attention to people who suffer from diseases that affect their mobility.

A Brain-Computer Interfaces

"Brain–computer interfaces (BCI's) give their users communication and control channels that do not depend on the brain's normal output channels of peripheral nerves and muscles." [1]. This is the most accepted definition of the so-called BCI's. In other terms, a BCI can detect the activation patterns of the brain, and whenever the user induces a voluntary modification of these patterns, the interface is able to detect it and to translate it into an action that is associated to the user's will.

Recent experiments have shown the possibility to use the brain electrical activity to directly control the movement of robots or prosthetic devices in real time [2]-[5]. Different experience on BCI technology has been gathered. In USA, the group of Wolpaw has develop a BCI based on variations of EEG rhythmic activity, capturing the signals by means of an electrode cap to control the movement of a cursor on a computer screen [6]-[8]. In Europe, the BCI system developed by the group of Pfurtscheller (Graz University) relays on an array with high number of electrode leads located over the scalp primary motor areas. They demonstrated that background EEG activity variation underlying motor imagery can control a prosthetic device for limited hand movements in a tetraplegic subject [9]-[10]. A different approach has been proposed by Birbaumer et al., (Tübingen University), utilizing a BCI based on the slow cortical potential that can open a communication channel with "locked-in" patients [11]-[13]. Finally, Millàn's group (IDIAP Research Center, Switzerland) has pioneered the use of BCI's to manipulate robots – a pocket-sized wheeled robot, a stand-in for a smart wheelchair, is directed to navigate its way through the rooms of a model house [14].

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Many other research group, more than it would be possible to review here, contributed to the advancement of the field. However, as it emerges from this concise review, control tasks based on human EEG have been addressed to simple application, such as moving a computer cursor [6], opening a hand orthosis [10], or drive a miniaturized wheeled robot. Beyond this pioneer approach, it is conceivable to extend the communication between disabled person and external environment towards mobility interaction. In particular, the recognition of mental activity will be put forward to guide devices (electronic wheelchair) or to interact naturally with common devices within the external word (telephone, switch; etc). This latter application of BCI technology has not been explored, yet; and it will represent the ultimate objective of this proposal.

B Robotics

The possibility of taking advantage of robotic technologies in the present research project stems from the fact that, in the last decades, the morphology of robots has undergone a remarkable mutation: from the fixed-base industrial manipulator, it has evolved into a variety of mechanical structures, characterized by the fact that the robot is capable of locomotion, either on wheels or legs. This ability has largely increased the domain of application of robots, once limited to the traditional factory environment, encompassing a number of different situations, including material and goods transportation, assistance to hospital patients and disabled people, automatic surveillance, space exploration and many others [14].

Navigation systems for sensor-based robot motion have made impressive advancements in recent years. Along the way, it has been necessary to address a number of theoretical and technological issues, such as:

- perception: the robot should be able to acquire a reliable local map of the surroundings using its sensory system [16];
- self-localization: to execute a given task, a precise estimate of the robot location in a world coordinate frame must be maintained [17];
- obstacle avoidance: unexpected or moving obstacles should be avoided by appropriate reactive manoeuvres [18];
- motion planning: on the basis of an environment map (local or global), the robot must plan movements leading to the destination, safely and efficiently [19];
- motion control: the accurate execution of movements (essential whenever the robot entrusts its own integrity to the sensory system) requires the development of effective feedback controllers whose performance must be robust with respect to perturbations [20].

While solutions are available for all the above problems, there is a gap to be filled concerning the application envisaged in the present project. In fact, the limited set of low-rate, high-level commands received from the user through the BCI must be integrated by an intelligence layer so as guarantee safe and efficient and task execution.

C. Assistive Technology

Assistive technology device means any item, piece of equipment, or product system, whether acquired commercially off-the-shelf, modified, or customized, that is used to increase maintain or improve the functional capabilities of an individual with a disability. Assistive devices can enhance the ability of an individual to perform everyday life activities, including interaction with the home environment.

Most homes today have appliances that allow for some degree of remote control - TV and hi-fi sets, air conditioning, alarm, etc. Domotics integrates and extends this ability throughout the house. A house with a domotics system probably will have at least one computer that will allow the homeowner to control different applications in various parts of the house remotely. A house that is equipped with a domotic system likely will have the ability to call the police or fire department by itself, unlike normal alarm systems. Domotic systems are often able to automatically gather data from several sensors and perform such things as adjusting lights, pull back curtains and lift window blinds without physical interaction. Also, the user can open and unlock or lock doors and gates remotely, control indoor temperature, set lights to go off, and doors to lock-all with a touch of a button. With a domotic system, you can even have your PC screen or TV set act as a home monitoring system, so that if someone is at the front door, you can see who it is without going to it. If you want to check what is going on in another room, you can do that with this system, provided that a compatible video camera is installed.

Though potentially useful for the disabled, those systems are not always designed to include the needs of this part of the population.

II. Overview Of The ASPICE Project

The ASPICE project (Assistive System for Patient's Increase of Communication, ambient control and mobility in absence of muscular Effort) has received in 2004 a renewable two-year funding grant from Italian medical research charity foundation TELETHON. The project

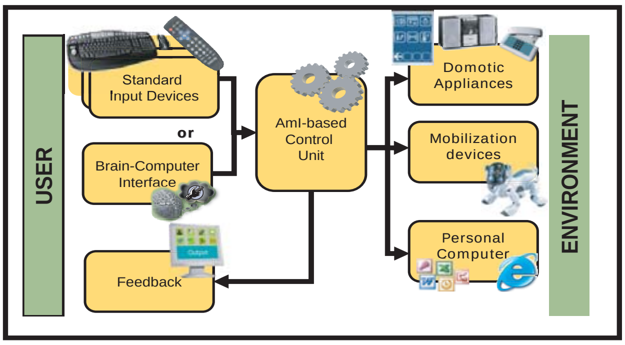

Fig. 1 Outline of the architecture of the ASPICE project. The figure shows that the system interfaces the user to the surrounding environment. The modularity is assured by the use of a core unit that takes inputs by one of the possible input devices and sends commands to one or more of the possible actuators. A feedback is provided to keep the user informed about the status of the system.

involves three partners, namely the Clinical Neurophysiopathology Laboratory at the Fondazione Santa Lucia IRCCS, the Robotics Laboratory by the Dipartimento di Informatica e Sistemistica of University of Rome “La Sapienza” and Telecom Italia Learning Services S.p.A.

The project is aimed at the development of a technological aid which allows neuromotor disabled persons to improve or recover their mobility and communication within the surrounding environment. This aim is particularly addressed towards those stages of the disease in which the residual muscular strength, if present, cannot be adequate for the utilization of conventional aids and in those conditions in which practical obstacles or security concerns could prevent a displacement from bed. The reduction of the patients’ independence involves a consequent increase of caregiver work load. Nowadays, Information Technology offers the chance to develop devices which, if correctly integrated, allow relief from the described limitations. The aid is being developed by integrating the expertise of the partners of the project. The key elements of the system are:

1) interfaces for easy access to computer: mouse, joystick, eye tracker, voice recognition, up to utilization of signals collected directly but non-invasevely from Central Nervous System (BCI);

2) controllers of intelligent motion devices which can follow complex paths, based on a small set of commands (Robotics);

3) information transmission and domotics, establishing an information flow between patient and controlled appliances, minimizing structural modifications of the house (Domotics).

The ASPICE architecture, with its input and output devices, is outlined in Fig. 1.

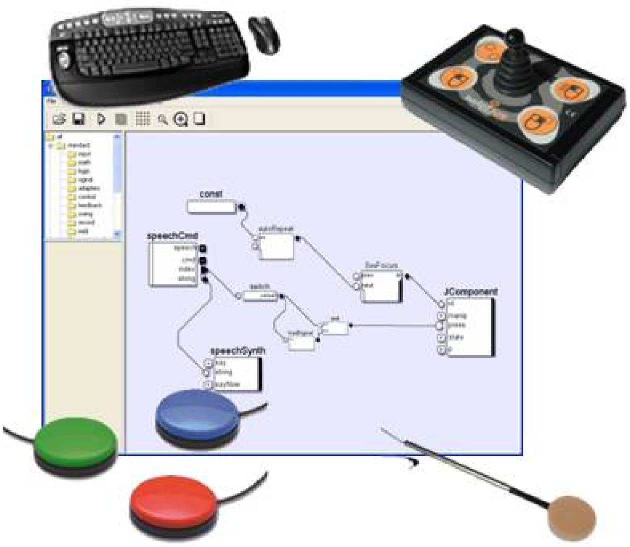

Fig. 2 Examples of input devices that have been interfaced to the Aspice system. From the top left, clockwise, a keyboard-mouse pair, a special joystick, a “leaf” button (can be operated with the neck), three pushbuttons (usually operated with the hand). In the background, the Graphical User Interface of the ICon package, that seamlessly connects several types of inputs to a ICon-aware module of the Aspice.

Achievements of the Project

At this stage of the project, a prototype of the system has been implemented and is available at the Fondazione Santa Lucia for the validation with patients.

In fact, a three-room space in the hospital has been furnished like a common house, and the actuators of the system have been installed afterwards. Care has been taken to make an installation that would be easily replicable in most houses. The place has been provided with a portable computer to run the core program, and several aids (input devices) are available to cope with as many categories of users as possible.

A Input Devices

The system input devices are customized on the motor users’ residual abilities. In fact users can utilize the aids they are already familiar with, and that have been interfaced to provide a low level input to a more sophisticated assistive device. On the other hand, the variety of input devices provides robustness to the patients’ abilities’ worsening, which is a typical consequence of degenerative diseases.

The software implementation of this modular attitude benefited from the use of the ICon package [21]

ICon is an editor designed to select a set of input devices and connect them to actions into a graphical interactive application. ICon allows physically challenged users to connect alternative input devices and/or configure their interaction techniques according to their needs. With the help of a technician for the configuration, it allows users to configure the Aspice application to use their favorite input devices and interaction techniques.

A non exhaustive list of input devices that have been successfully included follows:

- keyboard and mouse. Of course these are the most widely used input devices, and all users that are able to use them are incouraged to do so.
- Joystick, rollerball. If the loss of muscular strength makes the use of keyboard and mouse uncomfortable for the patient, or if spastic movements impede a correct use, devices like joysticks and rollerballs may reveal more appropriate.
- Touchpad. For those patients whose strength is too low to allow lifting arms, the touchpad (like the ones available on many laptop computers) allows to control the cursor with the movement of one finger.
- Head Tracker. If the motor disability is extremely impairing for the limbs, but the neck muscles are preserved, the user can use this device to control the cursor with the movements of the head.
- Microphone. Some users have a well preserved speech, which might reveal to be the most reliable way to send commands. A speech recognition engine translates phrases into commands for the core module.
- Joypads and Buttons. Joypads can be used to move the cursor towards the selected direction, almost like a joystick. Buttons can be used to send a very simple command – like “select” – or small sets of commands –

like “move forward” and “select”, if the patient can use two buttons. This kind of input must be used in conjunction with an appropriate feedback strategy, like a self-scanning set of icons. Buttons can be of the most diverse fashions, and actuated with the most disparate strategies (hand, elbow, chin, neck, teeth, puff), according to the most effective strategy for the individual users.

When the user is not able to use any of the above mentioned devices, or when a degenerative diseases makes likely that in the future he/she will no more be able, the support team proposes him/her to start training on the use of a BCI.

The BCI training is performed in a laboratory environment, through the use of the BCI2000 software package [22] and a clinical EEG equipment. When the user shows that he/she is able to select reliably one out of two or four possible items in this simplified environment, the BCI is connected to the Aspice system, and the user is asked to utilize the button interface (see Feedback section below) using the BCI control that he/she best masters.

B Core Operation

The system core receives the logical signals from the input devices and converts them into commands that can be used to drive the output devices.

Its operation is organized as a hierarchical structure of possible actions, whose relationship can be static or dynamic. In the static configuration, it behaves as a “cascaded menu” choice system. A xml initialization file, containing information about the structure is loaded upon login of the user, and is used to feed the Feedback module only with the options available at the moment (i.e. current menu). It will be duty of the Feedback module to choose the most appropriate representation of the available choices (i.e. a text menu, a set of icons, a topographical representation of the commands, etc).

In the dynamic configuration, an intelligent agent tries to learn from use which is the most probable choice that the user will make. This prediction can be made on the basis of (i) frequent sequences (after the user has turned the TV on, he most probably wishes to set the volume level); (ii) time of the day (at the twilight, the “light on” command has a higher probability; (iii) of environmental information (if the temperature is high, the user will probably wish to turn the fan on); (iv) of external events (if someone rings the door bell, almost surely the next commands will be “open the door”).

Whenever the user select an action that, rather than changing the internal context of the core (i.e. selects a non-leaf item of the cascaded menu), it instructs the system to undertake a physical action, the Control Unit fulfils the user’s demands by sending the appropriate control signals to the output appliances. Drivers are used to offer a homogeneous interface from the Control Unit’s point of view. In some cases, previously existing drivers are utilized for the devices, whereas in other cases (e.g. the robotic platform device) the driver has been designed “ad hoc” for the specific system.

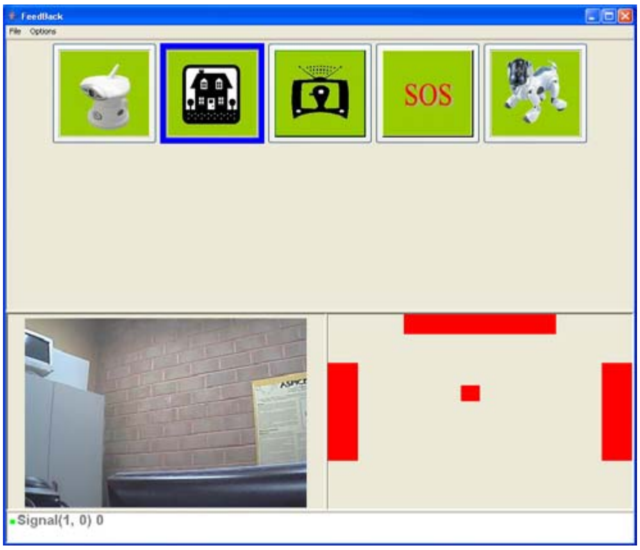

Fig. 3 Appearance of the feedback screen. The Feedback application has been instructed to divide the window into three panels. In the top panel, the available selections (commands) appear as icons. In the bottom right panel, a feedback stimulus by the BCI (matching the one the subject has been training with) is provided; the user uses his learnt modulation of brain activity to move the cursor at the center to hit either the left or the right bars – in order to focus the previous or following icon in the top panel – or to hit the top bar – to select the current icon. In the bottom left panel, the Feedback module displays the video stream from the video camera that was chosen beforehand in the operation.

C Feedback

The user can select the commands and monitor the system’s behavior through a Graphic Interface. Like all other modules, inter-module communication is transported via TCP/IP socket. This is most important in the case of the Feedback module, because this means that this module can run on a different computer from the one that is running the control unit. While, as mentioned, this is true for all modules, the Feedback can significantly benefit from this, since a lighter an low power computer such as a palmtop PC or even a smart phone can be used to give the subject the feedback he/she needs, while being of minimum burden for the user.

Figure 3 shows a possible appearance of the feedback screen. In this case, choices are pictured as button-shaped icons. This is possibly the most simple interface, and for sure the most practical to be operate with a reduced set of available input signals. In fact, in principle a user must only be able to master a single signal, that would be associated to the “select” action, leaving to the system the duty to move the focus on each icon for a pre-determined interval of time (auto-scan mode).

D Actuators

The Aspice system allows the user to operate remotely electric devices (e.g. TV, fan, lights) as well as monitoring the environment with remotely controlled videocameras. Moreover, a robotic platform can be controlled from the ASPICE Control Unit in order to accomplish few simple tasks.

While input and feedback signals are carried over a wireless (wifi or Bluetooth) communication, so that mobility of the patient is minimally affected, most of the actuation commands (with the obvius exception of the robot) are carried via a powerline-based control system, namely the X10.

X10 is a communications protocol that uses the house's electrical wiring as the medium for remote control of electrical systems. It was chosen since many components are available at a reasonable price, which is an uncommon circumstance for assistive devices. We have tested the benefits and the limits of this technology, and we are exploring other possibilities to cope with situations when the X10 is not advisable.

A non exhaustive list of electric and electronic devices that have been successfully interfaced to the system (through either a general purpose or a custom driver) is reported below.

- Ceiling neon lights. A X10 module has been installed in derivation to the wall switch. This required the intervention of a technician for a few minutes.
- Bulbs. Installation of X10 devices that can be interposed between a bulb and its socket require no technician to operate.
- TV set and HiFi set. The Aspice system is able to control any infrared remotely controlled (IRRC) appliance, thank to its IRRC emulator. A radio-wave repeater allows to control appliances that are not in the same room as the Central Unit computer.
- Motorized mattress. Low voltage motors were made controllable by interposing X10 modules between the tethered remote control and the motors. This required about two hours work by a technician.
- Buzzer. A X10 device that emits an alert sound can be placed in any room of the house (simply by plugging it into a mains socket) and operated at will.
- Door opener. A radio controlled device that turns a key in the keyhole has been interfaced with the system, allowing the user to open any door. Its installation requires no cabling or modification to the door.
- Network Cam. A motorized wifi network cam allows the user to watch a video stream of a wide set of wiews, which is usually one of the first actions that are lost by a movement impaired individual. Its installation is trivial, only requires a power source nearby, and can be configured in minutes.

Moreover, The Robotics Laboratory of University of Rome “La Sapienza” has developed a robot navigation system based on a small set of commands, which has been interfaced with the Aspice system. In fact, as previously mentioned, the system should cope with a variety of disabilities depending on the patients’ conditions. Therefore, three possible navigation systems have been designed for robot control. Firstly, the autonomous mode, which is based on high level commands (e.g. “walk to the window”) to drive the robot, should be used by very impaired patients’, which are unable to send frequent commands. Alternatively, depending on their residual abilities, patients can use a continuous directional joystick mode with basic obstacle avoidance, or a single step directional joystick to control the robot.

The Clinical Experimentation

The clinical experimental design has been curried out with the participation of subjects suffering from Spinal Muscular Atrophy type II (SMA II), Duchenne Muscular Dystrophy (DMD) and Amyotrophic Lateral Sclerosis (ALS). These neuromuscular diseases cause a severe global motor impairment which totally reduces the subject’s autonomy and creates a non-stop assistance condition as essential. The clinical experimentation has been taking place at the Santa Lucia Foundation where patients have been admitted for a neurorehabilitation program; the whole clinical experimental procedure underwent the approval of the local ethical commette. Accordingly, all patients have been informed on the nature of the developed device and on the modalities of the clinical experimentation and they gave their voluntary informed written consent. To this aim, we generated a booklet containing the project overview and the clinicians performing patients’ inclusion have been trained with all the required technical information. Once the patients had decided to participate to the study, the first step of the clinical procedure consisted of an interview and physical examination performed by the clinicians, wherein several levels of the variables of interest (and possible combinations) were addressed as follows:

- the degree of motor impairment and of reliance on the caregivers for everyday activities, as assessed by current standardized scale (Barthel Index (BI) for ability to perform daily activities);
- the use of and familiarity with transducers and aids (sip/puff, switches, speech recognition, joysticks) that can be used as input to the ASPICE system;
- the ability to speak or communicate, resulting comprehensible to an unfamiliar person (professional personnel have been devoted to monitor language ability);
- the level of informatics alphabetization, measured by the number of hours / week spent in front of a computer and by the fact that the patient works / used to work with a computer.

The second step consisted of the training with the ASPICE system. The training sessions have been integrated with the rehabilitation program as Occupational Therapy. For a period of time ranging from 3 to 4 weeks, the patient and (when required) her/his caregivers have been practising with the ASPICE system, installed into a house-like environment. During the whole period, even if more intensively at its beginning, patients have had the assistance of an engineer and a therapist in their interaction with the system. This experience has been conveyed into a manual of the system, for the advantage of users and installers, and into teaching guidelines, that are available for teachers with less experience.

Data on two main aspects have been collected during the experimentation:

- increase of the user’s independence

- reduction of caregivers' workload.

The index of daily activities performed (i) at the beginning of the training and (ii) when the user masters the system have been recorded and analyzed to evaluate the degree of effectiveness (ability to produce the desired result) of the system. In this regards, the individual degree of motor impairment and the used types of ASPICE inputs have been taken into account for system evaluation. Finally, a subjective index of satisfaction has been derived from a questionnaire administered both to the patient and to the caregivers.

CONCLUSIONS

The quality of life of an individual suffering from severe motor impairments is importantly affected by its complete dependence upon the caregivers. An assistive device, even the most advanced, cannot substitute – at the state of the art – the assistance provided by a human. Nevertheless, it can contribute to relief the caregiver from a continuous presence in the room of the patient, since the latter can perform some simple activities on its own, and most importantly, because the attention of the caregiver can be recalled by some form of alarm.

This means that in a clinical environment, the cost of assistance can be reduced, since the same number of paramedics or assistants can care after a higher number of patients (in non emergency conditions). In a home environment, the life of familiars can be less hardly affected by the presence of the impaired relative.

Most importantly, the perception of the patient is that he has no more to rely on the caregiver for each and every action. On one side this increases the sense of independence of the patient, on the other side this grants a sense of privacy, that is almost absent in the case another human has to take care. For both reasons, the quality of life of the patient is sensibly improved.

The ASPICE project innovates the concept of assistive technology device, bringing it to a system level – the user is no more given many devices to perform separate activities; rather the system provides unified (though flexible) access to all controllable appliances. Moreover we succeeded in the effort of including as many commercially available components in the system, so that affordability and availability of the components themselves is maximized.

The usefulness of the BCI-based interface has been recently investigated in other studies [23]. The improvement of quality of life brought by such a interface is expected to be relevant only for those patients who are non able to perform any voluntarily controlled movement. The advances in the BCI field are expected to increase the performance of this communication channel, thus making it effective for a broader population of individuals.

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