A Bi-Directional Interface Between the Human Nervous System and the Internet

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Abstract

This paper describes an investigation into the use of implant technology in forming a bi-directional link between the human nervous system and a computer. The microelectrode implant and the required neurosurgery are described in detail. Various application studies are described, including interaction with an articulated robot hand, a group of autonomous mobile robots and extra sensory (ultrasonic) signal inputs to the human nervous system. Conclusions are drawn, as a result of the study, as to the long term implant possibilities and future capabilities of those fitted with implants.

Introduction

Interaction between humans and computers is almost exclusively brought about by means of signals external to the human body [1], despite the fact that this causes time delays, errors and communication problems. The range of interaction tools is broad, including keyboard, joystick, voice activation and visual stimuli. In each case different translation and timing problems occur. The main problem is that electro-chemical signals on the human nervous system need to be translated into some form of mechanical or light energy before being converted back into electrical energy in the computer. The same and other problems are also encountered when signals are transmitted in the reverse direction from computer to human.

Substantial research is now ongoing in which biological signals are collected in a more direct way [2]. Unfortunately, because signals are measured externally to the human body, errors are induced because of the necessary energy transformations, overall neural signal averaging and the indirect nature of the measurements taken [3].

One line of present research involves the development of, what are described as, wearable computers [4]. These devices range from kitting out everyday implements such as shoes and jewellery with microcomputers, to directly monitoring indications of stress and alertness, and even to fitting a pair of glasses with a mini-television, allowing the wearer a remote televisual input. In reality all of these devices are far removed from the discussion in this paper, in that they are positioned externally to the human body, they operate on signals monitored on the outside of the body and returning signals need to be converted by the normal/usual human senses.

In order to investigate the practicalities of a more direct interface with computers, various animal studies have been carried out. Of relevance is the use of an extracted lamprey brain to control the movement of a small robot vehicle [5]. The lamprey is appears, has an innate response to light, which helps it to navigate in water, in particular to stay the right way up. This innate feature has been used to control the robot such that it always moves in the direction of a bright light source. Although it does function well, the trial is more a case of proving a point, as; unfortunately, the isolated lamprey brain only has a limited life span of, at most a few hours or so.

Research employing rats is also relevant and has been ongoing for some time. John Chapin chronically implanted electrodes into the motor cortex of rat’s brains [6] in order to decode neuronal activity immediately prior to a lever pulling exercise that the rates were trained for. Signals were processed, via the implant, before the rates actually pulled the lever and a reward was instantly given. Several of the rates learnt that they no longer had to actually pull the lever, but merely thinking about the action was sufficient to obtain the reward.

Of particular relevance to this article however, is the research of Philip Kennedy [7] whereby he enabled a brainstem stroke victim to control the movement of a cursor on a computer screen. Functional MRI scans were taken to decide on the best positioning for the electrode, since the patient had been asked to think about moving his hand. The electrode, which was positioned where neuronal activity was most pronounced, consisted of a hollow glass cone containing two gold wires. Meanwhile positioned on the outside of the patient’s head was an amplifier and radio transmitter. Subsequently, when the patient thought about moving his hand, so associated signals were transmitted to the computer to cause the cursor to move around, thereby enabling a basic form of communication.

Whilst it is certainly true that much work has also gone in to implant technology for such as retina and cochlea implants, it is felt that, although there may be some concepts to be learned from, in general the links with this study are not strong. Essentially we wish to investigate here an adaptable bi-directional link involving the computer. Such “replacement” implants do not exhibit such characteristics.

With the background of other research as described here, the main aim of the research discussed in this paper, was to form an operational adaptive bi-directional link between the human nervous system and a computer. To this end the first named author (KW) volunteered to receive an implant in his median nerve, the main group of nerve fibres running from the brain to the hand area. Details of the implant itself, and the operation, will now be given.

Microelectrode Implant

An array of one hundred individual needle electrodes was fired into the median nerve in the left arm of KW, just below the wrist, on March 14, 2002, at the Radcliffe Infirmary, Oxford, UK. The array measured 4mm x 4 mm with each of the, uniform length, pins being 1.55mm. The median nerve fascicle was approx 4 mm in diameter, hence the pins, when inserted, extended approx 40% of the way into the fascicle.

One incision, extending for 4 cm proximally, was made just below the wrist, with a second incision, extending for 2 cm, positioned centrally, 16 cm proximal to the wrist. An open tube was passed between the incisions, following a tunnelling procedure. The array, with associated wires, was then passed down the tube from the second incision to the first. Subsequently the tube was removed, leaving the array adjacent to the median nerve, with wires running subcutaneously up the arm, exiting at the second incision where they linked to an external electrical connector pad. The array was pneumatically inserted into the radial side of the median nerve bundle.

Bi-directional Signalling

By finger movements, neural signals, associated with the muscle contraction, could be generated and either passed directly to the computer, via an interface unit, or by means of a digital radio link, positioned on a gauntlet arrangement work externally [8]. By monitoring and processing these signals, in conjunction with a proportional-in-time controller, the movement, in terms of the associated neural signals, could be used to control a number of real-world devices.

A constant current stimulator was employed to stimulate the subpopulation of axons affected by the electrodes. Charge balanced, bi-phasic rectangular pulses of 200 usec duration were found to be best suited in allowing KW a stimulated sensation, hence enabling feedback from external mechanisms. Currents of below 80 uA in magnitude were seen to produce little effect, however at that current magnitude many of the electrodes produced a recordable effect.

Stimulation of this nature was first attempted six weeks after implantation. With the stimulation applied randomly, initial trials produced a correct identification over the range 68-73% of the time. Over the period of experimentation this response gradually improved. Final test, of the same nature, were carried out immediately prior to extraction of the implant, on June 18th 2002. At this time correct identification over the range 93-98% was witnessed. This indicates that KW's brain gradually learned to recognise the injected current signals more clearly.

Articulated Hand

Prosthetic hands are conventionally controlled by means of visual feedback to the operator, with an analogue input channel supplying a control signal to the hand generated from the electromyograms (EMGs) from forearm muscles. It is usual for them to be direct controlled in both opening and closing, hence 'Voluntary Opening Voluntary Closing' (VOVC). Essentially, if the user can see the articulated hand's actions and they can generate the appropriate muscular commands, they can operate a hand effectively. However without any internal intelligence or if the target object is obscured they may continue to close until the motor stalls, thus the prostheses cannot be easily controlled with finesse.

Natural hands are controlled in a hierarchical manner. Low levels of the central nervous system perform closed-loop control of individual fingers. Above this there is a coordinated action between the gripping force and the hand posture, minimising the grip force by maximising the contact area between the hand and the object. On a higher level still are the decision and planning areas of the brain, which deal with grasping strategy and use of the held object. The low level control is learnt in infancy.

Because subtle control of a conventional prosthetic hand often necessitates visual feedback it is hard to be controlled with the same low conscious effort and dexterity as a natural hand. In general they only have two motions (opening and closing), and one posture (precision grip) and hence exhibit a limited prehensile range. In comparison the type of articulated hand employed in this study has multiple degrees of freedom and can be controlled in a hierarchical manner, the aim of which is to mimic the control mechanisms apparent in a human hand. The prosthesis is currently undergoing clinical assessment in Oxfordshire, UK [9].

Using the articulated hand described, referred to as the SNAVE hand, allowed for measurements to be taken from force and slip sensors in the fingers. Further, the grip shape could be altered, as could the force applied to an object.

In the studies carried out, the SNAVE hand opening and closing movements were directly controlled from the neural signals of KW's own hand. So as KW opened and closed his own hand, the SNAVE hand mimicked movements in response to the neural signals being fed to it.

Following this, the objective was set to grasp an object, using the SNAVE hand, by using the lightest possible touch, without any visual feedback, whilst wearing a blindfold. As KW applied more force to an object, which could be detected via the hand fingertips, so this information was fed back through an increased amount of neural stimulation. Hence if the hand was applying the lightest possible touch, almost no neural stimulation was enacted.

After only 6 hours of learning to grip an object in this fashion, KW was able to achieve considerable success. Over the next 12 days of testing KW's ability to judge the appropriate force to apply improved more when both visual and force feedback were available, than with either feedback alone [10].

On May 20th, 2002, KW was situated in a laboratory in the Department of Computer Science, Columbia University, New York City. A link was established, by means of the Internet, between the implant and the SNAVE hand, still located at the University of Reading, UK. Processed signals from the neural implant were transmitted across the Internet to control the remote hand. Stimulation feedback was also provided, via the Internet, back to the implant. Allowing for the time delay present, due to the Internet, KW was able to operate the hand in a respectable fashion.

Autonomous Robots

In a separate study. Whilst the implant was in place, a small group of mobile, autonomous robots were controlled, in terms of their general ‘mood’, by means of signals from KW’s neural implant.

The robots permanently receive power from electrified strips in their flooring, via a set of electrical pick-up brushes. They are able to move around in their corralled environment by means of two separately excited, differentially driven rear mounted wheels, balanced at the front by a castor wheel.

Each robot contains ultrasonic range finders, which the robot uses to detect its distance from any solid object. The robots all also contain a circular array of infrared transmitters and receivers, which they use to find out the vicinity and identity of any other robots. The robots can communicate with each other by radio, and also to/from a PC/Base station. This station was also linked to the output from the implanted array.

The robots have a range of behaviours. At the bottom level is power seeking, then obstacle avoidance. At the next level is flocking or, its opposite, evasion, which means that the robots move away from each other as rapidly as possible.

Neural signals were taken from the implant to control the higher-level behaviour of the robots. Hence, by generating neural signals, KW was able to cause the robots to either flock together or evade each other. This example was taken to indicate how the same neural signals could be used to control the behaviour or response of a domestic robot in terms of its actions.

Extra Sensory Output

Ultrasonic sensors, identical to those employed by the autonomous robots, were fitted to a baseball cap work by KW. The output from the sensors was, in this case, fed down to the neural implant, via the interface unit such that if objects were located in the vicinity of the sensors, so the rate of current injection onto the nervous system was increased. As an object moved away from the sensors, so the rate of current injection decreased. The stimulation procedure was therefore similar to that used for force feedback signalling from the articulated hand.

With only a few minutes practice, wearing a blindfold along with the ‘ultrasonic baseball cap’, KW was able to successfully differentiate the distance of different objects, to the delimitation of the ultrasonic sensors themselves. In short while he was able to move around the laboratory and detect objects in doing so, with his new ultrasonic sense. It is felt that this sense could immediately be used, as a replacement, for blind people, but as an extra sense for others.

Other Applications

Other applications implemented using the array are presented in [11, 12]. In addition To the straightforward medical applications, however, one important issue is the use of implants on people who have no medical need, in order to enhance or augment their perceptual abilities. For example, the interface to the user employed an active ultrasonic sensor. A 40 KHz signal was broadcast from transducers worn on the head the reflected signal was detected and that was used to trigger a stimulation signal at the array, the frequency of the signal being proportional to the proximity of an object. This allows a form of ultrasonic vision to be applied. The same technique could be employed to establish and alternative sensor of vision to ameliorate visual impairment rather than to restore sight. It has some advantages over other remote ultrasonic sensors based on converting the ultrasound to audible sound [24] as the audible interfaces occupy a sense that the person is able to use effectively without a device, potentially actually *reducing* their capabilities. The implant would allow input channels unavailable or unoccupied to be employed fully.

One of the key aspects of the project was however to see how the implant might be useful for those who have a disordered nerve function, for example [taken from 11]:

1. Re-education of the brain and spinal cord
2. Prevention of spinal deformity
3. Treatment of intractable neurogenic and other pain
4. Assisting bladder emptying
5. Improving bowel function
6. Treatment of spasticity
7. Improvement of respiratory function
8. Redirection of cardiovascular maleffect
9. Prevention of pressure sores through sensory feedback
10. Improvement/restoration of sexual function
11. Improved mobility
12. Improvement in activities of daily living

In addition, via the bi-directional radio link, it was possible for the user to switch on lights and other general household appliances, directly from translated neural signals. General control of a local/household environment for those with mobility impairment, such as the elderly and/or disabled can also be seen as possible application.

Conclusions

It is quite possible to make direct connection with the human nervous system, to control technology directly from neural signals and to feedback signals onto the nervous system, which relate directly to external, real world artefacts. Passing these signals across the Internet implies that the implanted individual's nervous system extends, across the Internet, outside their regular body. Controlling an articulated hand directly from neural signals, 3,500 miles away, across the Internet was testimony to that.

Although ultrasonic signals were successfully employed as an extra sense, this opens up the possibility of a wide range of different senses for humans, including infrared and x-rays. These will provide an exciting range of experiments in the years ahead.

One down side with the implant experiments carried out was mechanical fatigue in the implant connecting wires. Whilst the array itself, lasted well, the connecting wires gradually became open-circuit at their point of exit from the body. It is felt that when a full implant is employed this problem ill either be considerably reduced or even completely removed all together.

Successful though this project was felt to be by the authors, the follow up experiment will necessarily involve a direct implant, or implants, into the brain. Direct thought control and thought enhancement appear to be achievable, but these will require implants directly into the bran, rather than merely the nervous system.

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