Thought communication and control: a first step using radiotelegraphy

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Abstract: A signalling procedure is described involving a connection, via the Internet, between the nervous system of an able-bodied individual and a robotic prosthesis, and between the nervous systems of two able-bodied human subjects. Neural implant technology is used to directly interface each nervous system with a computer. Neural motor unit and sensory receptor recordings are processed real-time and used as the communication basis. This is seen as a first step towards thought communication, in which the neural implants would be positioned in the central nervous systems of two individuals.

1 Introduction

Significant levels of research are currently being undertaken in which biological signals are collected in some form, operated upon by appropriate signal processing techniques and then used to either control a device or as an input to some type of feedback mechanism [1, 2]. In the majority of cases the signals are measured outside the body, which in itself presents a plethora of communication and measurement problems [3, 4]. Whatever external sensory system is used, losses and errors occur due to the signal attenuation through the body and inherent noise issues associated with small signal detection. Similarly, problems arise when translating electrical energy from the computer to the electrical energy that is apparent on the nervous system, via an intermediate form, for example mechanical vibration or thermal variation, to utilise the sensory receptor channels.

Wearable computers provide perhaps one of the closest external links between man and machine. With everyday items such as shoes and glasses being augmented with microcomputers [5, 6], indications of stress and alertness can be monitored and the state of the device altered to affect the wearer. One of the most widely reported applications of this class involves the use of a miniature computer screen fitted onto an otherwise standard pair of glasses. In this way the wearer can be given remote vision [7] or additional information about the scene can be relayed. In all cases however, although positioned adjacent to the body, they still require signal conversion to take place to interface the technology with the human sensory receptors. Of much greater interest are studies in which a direct link is formed between the nervous system and the technology.

To this end, numerous animal studies have been carried out (see [8] for a review). As an example, the extracted brain of a lamprey has been used to control the movement of a

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small-wheeled robot [9]. This procedure utilises the fact that the innate response of a lamprey is to position itself in water by detecting and reacting to light playing on the water surface. So, when surrounded by a ring of lights this unconditioned behaviour is decoded to motion commands to move the robot round the arena towards the active light source.

Research using rats is also of interest. Two studies of particular relevance were both inaugurated by John Chapin at the MCP Hahnemann School of Medicine, Philadelphia. In the first study [10], an environment was created such that when rats pulled a lever they received a reward: a tot of water. By chronically implanting electrodes in the motor cortex of the rat's brains and decoding the neuronal population activity, signals could be extracted directly when the rat thought about pulling the lever, but before any physical movement occurred. This information was used to directly release the reward before the rat pulled the lever. Over the period of a few days, four of the six rats in the experiment learned that they need not initiate the action in order to obtain the reward; merely thinking about it was sufficient.

In the second study [11], Chapin showed how direct brain stimulation of rats could be employed in order to teach them to solve a maze problem. Essentially, reinforcement learning was employed with pleasurable stimuli evoked when a rat moved in the correct direction.

The purposes for the integration of technology with the human central nervous system (CNS) have varied from the diagnostic [12] to the amelioration of symptoms [13-15], to the augmentation of the existing senses [16, 17] and to allow an easier or more seamless operation of the computer technology. Perhaps the most widely reported research involving human subjects is that based on the development of an artificial retina [18]. In this work, small arrays have been successfully attached to a functioning optic nerve, but where the person has no vision. With direct stimulation of the nerve with the correct signal sequences it has been possible for the user to perceive shapes and letters. Such experiments have now been conducted for well over a decade. The signal processing and stimuli form has improved through successive generations of the associated software, taking advantage of both the improved understanding of the human visual system and knowledge gained through the experimentation, and some adjustment of the

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system specific to the users involved. However, it is clear that this approach cannot yet instantly restore even a limited form of sight.

Electronic neural stimulation has proved to be successful in other areas, with applications ranging from cochlea implants to the treatment of Parkinson's disease symptoms. The most relevant to this study, however, is the use of a brain implant, which enables a brainstem stroke victim to control the movement of a cursor on a computer screen [19]. Prior to the implantation, functional magnetic resonance imaging of the subject's brain was made. When the subject was asked to think about moving his hand the fMRI scanner was used to localise where the activity was most pronounced. A hollow glass electrode cone containing two gold wires (neurotrophic electrode) was implanted into the motor cortex and positioned in the areas of maximumrecorded activity.

With the electrode in place, when the patient thought about moving his hand the output from the electrode was amplified and transmitted by a radio link to a computer where the signals were translated into control signals to enable movement of the cursor. The subject successfully learnt to move the cursor around by thinking about different movements. The neurotrophic electrode uses tropic factors to encourage nerve growth in the brain. Over the period that the implant was in place, no rejection of the implant was observed; indeed the neurons grew into the electrode allowing stable long-term recordings.

It is clear that studies such as those in [19] implement a unidirectional form of radio communication between the human nervous system and a computer. In this sense the implant research conducted is distinctly different from the practical realisation of 'replacement' implants for dysfunctional cochlea or retina augmentation.

With this as a state of the art starting point, a key aim of the research described in this paper is the eventual realisation of a bidirectional radio link between the brains of two individual humans. What is described here is the first step along this path, namely telegraphic communication between two individuals by a real-time connection via a computer between their nervous systems.

What will be described in the following Section is the microelectrode array (MEA), which was implanted into a human nervous system to act as the silicon/biological interface. Subsequently, a pilot study is described utilising the Internet as a transport layer to send signals generated from the human nervous system to and from a remote location in order to operate and receive feedback from an articulated robotic hand. Finally, an experiment is presented in which signals were sent by RF link between the nervous systems of two humans.

2 Microelectrode array

In general there are two types of peripheral nerve interfaces, extraneural and intraneural. The most common extraneural device is the cuff electrode, which fits snugly around the nerve trunk, allowing for the recording of the sum of the single fibre action potentials, known as the compound action potential (CAP). This can be used for recording or for crudely selective neural stimulation of a large region of the nerve trunk. In some cases the cuff can contain a second or more electrodes fitted distally, allowing for a rough measurement of signal speed travelling down the nerve fibres.

Of more practical use in applications which require a much finer granularity of neural signal for both selective monitoring and stimulation is an intraneural interface, such as the microelectrode array (MEA). The MEA employed in this work contains a total of 100 electrodes which, when implanted, become distributed within the nerve fascicle. By this means, access can be gained to muscle spindles, motor neural signals to particular motor units and sensory receptors. Essentially such a device allows a bidirectional link between the human nervous system and a computer [20–22].

On 14 March 2002, during a two-hour procedure at the Radcliffe Infirmary, Oxford, an MEA was surgically implanted into the median nerve fibres of the left arm of the first named author (KW). The array measured $4 \text{ mm} \times 4 \text{ mm}$ with each of the electrodes being 1.5 mm in length. With the median nerve fascicle estimated to be 4 mm in diameter, this meant that the electrodes penetrated well into the fascicle. The array was pneumatically inserted into the median nerve fibres with the electrodes penetrating into the fascicle.

The array was positioned just below the wrist, following a 4 cm long incision. A further incision, 2 cm long, was made 16 cm proximal to the wrist. The two incisions were connected by a tunnelling procedure such that wires from the array ran up the inside of the left arm where they exited and connected onto an electrical terminal pad which remained external.

The arrangements described remained permanently in place for 96 days, until 18 June 2002, at which time the implant was removed.

3 Signal recording and nerve stimulation

The array, once in position, could act as a bidirectional neural interface. Neural signals could be transmitted directly from the peripheral nervous system to a computer by means of either a hard wire connection or through a radio transmitter/receiver unit. The signals which could, in the first instance, be monitored from the small collection of axons around each of the electrodes, were generated by straightforward finger movements. It was found that, due to the positioning of the array, movement of the left index finger produced particularly prominent results.

Typical activity occurred around a centroid frequency of approximately 1 kHz and it was noted that signals of apparent interest occurred well below 3.5 kHz. Conversely noise was a distinct problem due to inductive pickup on the wires linking the array to the connector pad. This noise needed to be severely reduced and to this end a fifth-order band-limited Butterworth filter was used with corner frequencies of $f_{low} = 250 \text{ Hz}$ and $f_{high} = 7.5 \text{ kHz}$. To help reduce the noise pickup from the umbilical wires between the implanted electrode array and the bank of filters, and to allow freedom of movement, a small wearable radio device was developed to be worn on a gauntlet around the wrist. This custom hardware consisted of a 20-way multiplexer, two independent filters, two 10 bit A/D converters, a microcontroller and an FM radio transceiver module. Either one or two electrodes from the array could be quasistatically selected, digitised and sent over the radio link to a corresponding receiver connected to a PC. At this point they could either be recorded or transmitted further in order to operate networked technology, as described in the following Section. Onward transmission of the signal was via an encrypted TCP/IP tunnel, over the local area network, or wider Internet. Remote configuration of various configuration parameters on the wearable device was also possible via the radio link from the local PC or the remote PC via the encrypted tunnel.

Stimulation of the nervous system by means of the array is much more problematic due to the extremely limited nature of existing results using this type of interface. Published work is restricted largely to a respectably thorough but short-term study into the stimulation of the sciatic nerve in cats [21]. Experimental time was therefore required, on a trial and error basis, to ascertain what voltage/current relationships would produce a reasonable (i.e. perceivable, but not painful) level of nerve stimulation.

Further factors which may well emerge to be relevant, but were not possible to predict in this experimental session, were:

(a) the plastic, adaptable nature of the human nervous system and the brain, even over relatively short periods; and(b) the effects of movement of the array in relation to the nerve fibres, hence the connection and associated input impedance of the nervous system was not completely stable.

After extensive experimentation it was found that injecting currents below $80 \,\mu\text{A}$ onto the median nerve fibres had little perceivable effect. Between $80 \,\mu\text{A}$ and $100 \,\mu\text{A}$ all the functional electrodes were able to produce a recognisable stimulation, with an applied voltage of $40-50 \,\text{V}$, dependant on the series electrode impedance. Increasing the current above $100 \,\mu\text{A}$ had little additional effect; the stimulation switching mechanisms in the median nerve fascicle exhibited a nonlinear thresholding characteristic.

In all successful trials, the current was applied as a biphasic signal with pulse duration of $200 \,\mu\text{s}$ and an interphase delay of $100 \,\mu\text{s}$. A typical stimulation waveform of constant current being applied to one of the MEA's implanted electrodes is shown in Fig. 1.

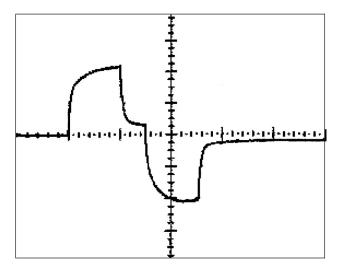


Fig. 1 Voltage profile during one biphasic stimulation pulse cycle with a constant current of $80 \,\mu A$ Vertical scale: $10 \,\text{V/div}$ Horizontal scale: $200 \,\mu\text{s/div}$

It was therefore possible to create alternative sensations via this new input route to the nervous system, thereby bypassing the normal sensory inputs.

4 Internet experiment

On 20 May 2002 a link was established between the implanted array in Columbia University, New York City, USA, and an articulated hand [23] in Reading University, UK.

The hand has multiple degrees of freedom, its aim being to mimic as closely as possible the control mechanisms as they occur in a human hand. In normal operation, sensors in the articulated hand's fingertips allow for the shape of grip to be modified to the object being held and for the force applied via the fingertips to be altered as necessary. In this way the amount of tension applied by the hand to an object can be changed in order to either apply an appropriate force to a hard/soft object being held or specifically to prevent the object from slipping. The intelligent hand prosthesis is shown in Fig 2.



Fig. 2 Intelligent articulated robotic hand prosthesis

In the first stages of the experiment, filtered neural signals from the implant were transmitted across the Internet to control the articulated hand at its remote location. Essentially, as KW opened and closed his hand in New York, the neural signals which directed these movements were also transmitted to the UK via the Internet to bring about a form of tele-operational articulated hand motion. Both the articulated and human hand were being controlled by the same neural signals. Within a short time of adjusting tolerance on the software controlling the articulated hand's movements, a >95% success rate in sympathetic movement was achieved.

Coupled with this, sensory data from the articulated hand's fingertips were fed back across the Internet to bring about stimulation of the nervous system. So with KW blindfolded, i.e. without any visual stimuli, success was achieved in perceiving the stimulation and thus controlling the articulated hand.

5 Human-to-human communication

On 10 June 2002, a second recipient (IW, wife of KW) had two active electrodes inserted into the median nerve of her left arm, a process termed microneurography, approximately at the same location as the first recipient's implant. To ensure the electrodes were correctly positioned within the median nerve, the procedure was conducted without anesthetic. A further reference electrode was inserted 4 cm further up the arm adjacent, but without penetrating, the median nerve.

During recording, neural signals were monitored via one of the microneurography electrodes. Stimulation parameters similar to those used with the MEA achieved perceivable sensation.

Neural signals produced as a result of KW's finger movements were transmitted, via the internet to IW's implanted electrodes to cause stimulation of her nervous system. Similarly, neural signals transmitted from IW's nervous system across the Internet were used to stimulate KW's nervous system. In a series of double-blind tests, sets of signals were transmitted between the two individuals and were successfully identified. For example, when IW generated three motor neural signal pulses, three nervous system stimulation pulses were perceived by KW and vice *versa*. This was achieved with >98% accuracy.

6 Discussion

What was achieved in this experiment was essentially a form of radiotelegraphy signalling between the nervous systems of two human subjects. The coding employed was simply proportional and the signals were readily recognisable to both the human subjects involved.

The next step in this research involves the use of implants, possibly similar to that used with KW, positioned not in the peripheral nervous system but rather directly in the brain motor cortex region, rather akin to the single electrode implant already achieved in [19]. With two human recipients so implanted it should then be possible not only to repeat the set of experiments described in this paper but to work towards a more complex coding scheme. In essence, the signalling system will be direct from brain to brain and will be initiated by neural signal transmission/reception. As described in [19] such signals are generated when an individual 'thinks' about moving.

A major long-term research question is that if implants are positioned not in the motor neuron region but elsewhere in the brain, what variety and range of thoughts can be transmitted and what might these mean to the recipient? For example, can some form of signals related to memories be ultimately transmitted? It is not the purpose here to describe basic brain functioning, however suffice to say that the operation of the brain is based on electrochemical signals and any thoughts that originate have an electrochemical basis.

Just as the basic functioning of the original telegraph system, and subsequently telephones, are based on the conversion between electrical and mechanical systems, so in this paper a signalling system has been described which involves electrical and chemical signals and their cooperation.

One aspect of this study is the potential use of these types of implants to help those with a lesion in their nervous system. The aim being to bring about some otherwise missing movement; to return control of the body functions to the body's owner; or to allow a recipient to control technology around them. In the case of the experiments described, an articulated robot hand was controlled directly by neural signals. For someone who has had their original hand amputated, this opens up the possibility of them ultimately controlling an articulated hand, as though it were their own, by the power of their own thought.

A further aspect of the research was to investigate the human body's acceptance or rejection of such an implant. No infection was witnessed during the course of the experiment and during extraction it was observed that tissue had grown around the array holding it in its original place.

It is recognised that as far as thought communication is concerned, what has been achieved is an extremely primitive first step. Indeed it may well be the case that implants of the type used here are not ultimately those selected for a good bidirectional link between the human brain and a computer. Nevertheless the results obtained were extremely encouraging and lead one to hope that a rich form of thought communication will be possible in the future.

7 **Further comments**

It is clear that the experimental work described in this paper has considerable implications [24]. For example, remote controlling an articulated hand in the way described is fine in terms of helping to restore movement for those who have a lesion in their nervous system. At the same time the technology allows an individual to control technology at a remote location, directly by neural signals, the Internet acting merely as an extension to their nervous system. It also allows, however, for the potential remote control of an individual's movements either by a machine or by another human

But with more than one brain linked onto the Internet, the ethical questions are even more profound. Whilst altering privacy as it now stands, the whole basis for communication between individuals can possibly change dramatically. In this paper an operational telegraphic system between nervous systems has been described. If this can subsequently be developed into a telephonic system and ultimately into a telequalic system in which individual thoughts (qualia) can be transmitted between human brains, then clearly it may have a profound effect on the meaning of humanity.

One final point that should be stressed is that the biotechnological interface, when using implant technology, is a large area for future research. Clearly longer-term studies will need to be carried out in order to perform successful brain implant studies in which removal of the implant after a period may well not be possible due to potential trauma. It was clear in our own studies that the nervous system of Kevin Warwick adapted in a positive way in response to the bidirectional experimental studies being carried out. It will be interesting to investigate if such a positive change is witnessed with all implanted individuals or whether distinct differences are exhibited.

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References 9

- 1 Penny, W.D., Roberts, S., Curran, E., and Stokes, M.: 'EEG-based Rehabil. Eng., 2000, 8, pp. 214–215
 Poulton, A., Kyberd, P.J., and Gow, D.: 'Progress of a modular prosthetic arm'. Presented at 1st Cambridge University Workshop on
- 2 Advances in Assistive Technology, Cambridge, UK, March 2002

- Wolpaw, J., McFarland, D., Neat, G., and Forheris, C.: 'An EEG 3 based brain-computer interface for cursor control', Electroencephalogr.
- *Clin. Neurophysiol.*, 1990, **78**, pp. 252–259 Kubler, A., Kotchoubey, B., Hinterberger, T., Ghanayim, N., Perelmonter, J., Schauer, M., Fritsch, C., Taub, E., and Birbaumer, N.: 'The thought translation device: a neurophysiological approach to communication in total motor paralysis', *Exp. Brain Res.*, 1999, **124**, 4 op. 223–232
- Paradiso, J.A., Hsiao, K., Benbasat, A.Y., and Teegarden, Z.: 'Design 5 and implementation of expressive footwear', IBM Syst. J., 2000, 39,
- 6 7
- 8
- and implementation of expressive footwear, *IBM Syst. J.*, 2000, *39*, (3/4), pp. 511–529 Thorp, E.: 'The invention of the first wearable computer'. Proc. 2nd Int. Symp. on Wearable Computers, Oct. 1998, pp. 4–8 Mann, S.: 'Wearable computing: a first step towards personal imaging', *Computer*, 1997, **30**, pp. 25–32 Warwick, K.: 'I, cyborg' (Century, 2002) Reger, B., Fleming, K.M., Sanguineti, V., Simon Alford, S., and Mussa-Ivaldi, F.A.: 'Connecting brains to robots: the development of a hybrid system for the study of learning in neural tissues'. Presented a hybrid system for the study of learning in neural tissues'. Presented at Artificial Life VII, Portland, OR, USA, August 2000 Chapin, J.K., Markowitz, R.A., Moxon, K.A., and Nicolelis, M.A.L.:
- 10 Direct real-time control of a robot arm using signals derived from neuronal population recordings in motor cortex', *Nat. Neurosci.*, 1999, **2**, pp. 664–670
- Talwar, S.K., Xu, S., Hawley, E.S., Weiss, S.A., Moxon, K.A., and Chapin, J.K.: 'Rat navigation guided by remote control', *Nature*, 11 2002, 417, pp. 37–38 Denislic, M., and Meh, D.: 'Neurophysiological assessment of
- 12
- Denishe, M., and Mell, D.: Neurophysiological assessment of peripheral neuropathy in primary Sjögren's syndrome', J. Clin. Investig., 1994, 72, pp. 822–829 Poboroniuc, M.S., Fuhr, T., Riener, R., and Donaldson, N.: 'Closed-loop control for FES-supported standing up and sitting down'. Proc. 7th IFESS Conf., Ljubljana, Slovenia, 2002, 2007. 13 pp. 307-309

- Popovic, M.R., Keller, T., Moran, M., and Dietz, V.: 'Neural 14
- Popovic, M.R., Keller, T., Moran, M., and Dietz, V.: 'Neural prosthesis for spinal cord injured subjects', *J. BioWorld*, 1998, **1**, pp. 6–9 Yu, N.Y., Chen, J.J., and Ju, M.S.: 'Closed-loop control of quadriceps/hamstring activation for FES-induced standing-up movement of paraplegics', *J. Musculoskelet. Res.*, 2001, **5**, (3) Cohen, M., Herder, J., and Martens, W.L.: 'Cyberspatial audio technology', *J. Acoust. Soc. Jpn.*, 1999, **20**, (6), pp. 389–395 Butz, A., Hollerer, T., Feiner, S., McIntyre, B., and Beshers, C.: 'Enveloping users and computers in a collaborative 3D augmented reality' Proc. IWAR99 San Francisco CA USA 20–21 October 15
- 16
- reality'. Proc. IWAR99, San Francisco, CA, USA, 20-21 October
- Kanda, H., Yogi, T., Ito, Y., Tanaka, S., Watanabe, M., and Uchikawa, Y.: 'Efficient stimulation inducing neural activity in a retinal implant'. Proc. IEEE Int. Conf. on Systems, Man and 18 Cybernetics, Tokyo, Japan, 1999, Vol. 4, pp. 409–413 Kennedy, P., Bakay, R., Moore, M., Adams, K., and Goldwaithe, J.:
- 19 Direct control of a computer from the human central nervous system', *IEEE Trans. Rehabil. Eng.*, 2000, **8**, pp. 198–202 Gasson, M., Hutt, B., Goodhew, I., Kyberd, P., and Warwick, K.: 'Bi-directional human machine interface via direct neural connection'.
- 20 Proc. IEEE Workshop on Robot and Human Interactive Communication, Berlin, Germany, Sept. 2002, pp. 265–270 Branner, A., Stein, R.B., and Normann, E.A.: 'Selective stimulation of
- 21
- Mannet, A., Soln, YE, and Young, and Young 22
- Kyberd, P., Evans, M., and te Winkel, S.: 'An intelligent anthropomorphic hand with automatic grasp', *Robotica*, 1998, **16**, 23 pp. 531–536
- Warwick, K.: 'Cyborg morals, cyborg ethics, cyborg values', *Ethics Inf. Technol.*, 2003, **5**, (3), pp. 131–137 24