The Diminishing Human-Machine Interface

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Summary

In this article a look is taken at interfaces between technology and the human brain. A practical perspective is taken rather than a theoretical approach with experimentation reported on and possible future directions discussed. Applications of this technology are also considered with regard to both therapeutic use and for human enhancement. The culturing of neural tissue and its embodiment within a robot platform is also discussed, as are other implant possibilities such as permanent magnet implantation, EEG external electrode monitoring and deep brain stimulation. In each case the focus is on practical experimentation results that have been obtained as opposed to speculative assumptions.

Introduction

Over the last few years tremendous advances have been made in the area of human-computer interaction, particularly insofar as interfaces between technology and the body or brain are concerned. In this article we take a look at some of the different ways in which such links can be forged.

Considered here are several different experiments in linking biology and technology together in a cybernetic fashion, essentially ultimately combining humans and machines in a relatively permanent merger. It is important to realise that a key driver in this is that it is the overall final system that is important. Essentially, from a biological start point, by coupling in a relatively permanent way, with technology so the overall system can exhibit many more functions than the original biological entity. This can be realised for purposes of therapy alone, however much more exciting is the fact that it opens up the opportunity for human enhancement.

Where a brain is involved, which surely it is somewhere, it must not be seen as a stand alone entity but rather as part of an overall system – adapting to the system's needs – the overall combined cybernetic creature is the system that is of importance.

Each of the experiment is described in its own separate section. Whilst there is, in some cases, a distinct overlap between the sections, they each throw up individual considerations. Following a description of each investigation some pertinent issues on the topic are therefore discussed. Points have been raised with a view to near term future technical advances and what these might mean in a practical scenario. It has not been the case of an attempt here to present a fully packaged conclusive document, rather the aim has been to open up the range of research being carried out, see what's actually involved and look at some of its implications.

We start by looking at research into growing brains within a robot body, move on to the Braingate, take in deep brain stimulation and (what is arguably the most widely recognised) eeg electrode monitoring and conclude with permanent magnet implantation which is being classified nowadays as "BioHacking" in the popular press. This later method can probably be seen as an entry level implant, so to speak. RFID implants are also briefly discussed.

Biological Brains in a Robot Body

Neurons can be cultured under laboratory conditions on an array of non-invasive electrodes. Whilst it is certainly possible to investigate their development per se, without embedding them within an active feedback loop results are likely to be somewhat stilted. A more sensible and useful route is to culture the neurons such that they can operate within a real world body. A robot body can move around in a defined area under the control of such a network/ /brain and the effects on the brain, due to controlling the body, can be witnessed. Whilst this is, in itself, extremely interesting from a robotics perspective, it also opens up a new approach to the study of the development of the brain itself because of its sensory--motor embodiment. Investigations can therefore be carried out into such as memory formation and reward/punishment scenarios and other elements that underpin the basic functioning of a brain.

Growing brain cells (around 100,000 at present) in vitro commences by separating neurons obtained from foetal rodent cortical tissue. They are then grown in a small dish which is housed in an incubator in which they are provided with suitable environmental conditions and nutrients as a food stock. An array of electrodes embedded in the base of the dish (a Multi Electrode Array; MEA) acts as a bi-directional electrical interface to and from the culture. This enables electrical signals to be supplied to stimulate the culture and also for recordings to be taken as outputs from the culture.

The neurons in such cultures spontaneously connect, communicate and develop, within a few weeks giving useful responses for typically 3 months at present. The flat '8x8' Multi Electrode Array can be used for real-time recordings (see Figure 1). In this way

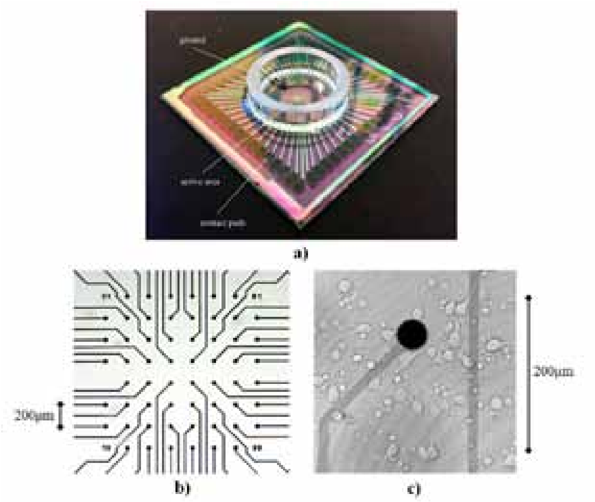

Figure 1: a) A Multi Electrode Array (MEA) showing the electrodes b) Electrodes in the centre of the MEA seen under an optical microscope c) An MEA at x40 magnification, showing neuronal cells in close proximity to an electrode.

it is possible to separate the firings of small groups of neurons by monitoring the output signals on the electrodes. A picture of the global activity of the entire network can thus be formed. It is also possible to electrically stimulate the culture via any of the electrodes in order to induce neural activity. The multi--electrode array therefore forms a bi-directional interface with the cultured neurons [1, 2].

Once it has developed for about 10 days or so the brain can be linked to its physical robot body [3] with signals being transmitted from the brain to the robot body to effect its movement. Sensory data fed back from the robot is subsequently delivered to the culture, thereby closing the robot-culture loop. Thus, the processing of signals can be broken down into two sections (a) 'culture to robot', in which live neuronal activity is used as the decision making mechanism for robot control, and (b) 'robot to culture', which involves an input mapping process, from robot sensor to stimulate the culture.

The actual number of neurons in a brain depends on natural density variations in seeding the culture in the first place. The electrochemical activity of the culture is sampled and this is used as input to the robot's wheels. Meanwhile the robot's (ultrasonic) sensor readings are converted into stimulation signals received by the culture, thereby closing the loop.

Early development of the culture involves the formation of elementary neural connections. An existing neuronal pathway through the culture is identified by searching for strong relationships between pairs of electrodes. Such pairs are defined as those electrode combinations in which neurons close to one electrode respond to stimulation from the other electrode at which the stimulus was applied more than 60% of the time and respond no more than 20% of the time to stimulation on any other electrode.

A rough input-output response map of the culture is drawn by cycling through the electrodes in turn. In this way, an input/output electrode pair can be chosen in order to provide an initial neural pathway for the robot to operate. This is then employed to control the robot body – for example if the ultrasonic sensor is active and we wish the response to cause the robot to turn away from the object being located ultrasonically (possibly a wall) in order to keep moving.

For simple experimentation purposes, the small wheeled robot (see Figure 2) is required to follow a forward path until it reaches a wall, at which point the front sonar value decreases below a threshold, set at something like 20 cm., triggering a stimulating pulse. If, shortly after this, the responding (output) electrode registers activity so the robot turns to avoid the wall. In experiments the robot turns whenever activity is registered on the response electrode. The most relevant result is therefore the occurrence of the chain of events: wall detection–stimulation–response.

As an overall control element for direction and wall avoidance the cultured brain acts as the sole decision making entity within the overall feedback loop. One important aspect for investigation involves neural pathway changes, with respect to time, in the culture between the stimulating and recording electrodes.

In terms of research, learning and memory investigations are at an early stage. However the robot can be seen to improve its performance over time in terms of its wall avoidance ability in the sense that neuronal pathways that bring about a satisfactory action tend to strengthen purely though the process of being habitually performed – learning due to habit.

The number of variables involved is though considerable and the plasticity process, which occurs over quite a period of time, is dependent on such factors as initial seeding and growth near electrodes as well as environmental transients such as temperature and humidity. Learning by reinforcement – rewarding good actions and punishing bad is more in terms of investigative research at this time.

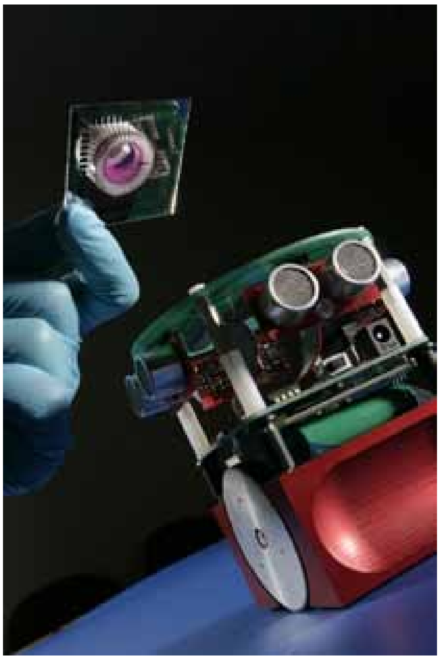

Figure 2: Wheeled Robot Body and Brain Together

It has been shown that a robot can have a biological brain with which to make its 'decisions'. The 100,000 neuron size is merely due to the present day limitations of the experimentation described. Indeed 3 dimensional structures are already being investigated. Increasing the complexity from 2 dimensions to 3 dimensions produces a figure of approximately 30 million neurons for the 3 dimensional case – not yet the 100 billion neurons of a 'perfect' human brain, but well in tune with the brain size of many other animals.

This area of research is expanding rapidly. Not only is the number of cultured neurons increasing, but the range of sensory inputs is being expanded to include audio, infra red and even visual. Such richness of stimulation will no doubt have a dramatic effect on culture development. The potential of such systems, including the range of tasks they can deal with, also means that the physical body can take on different forms. There is no reason, for example, that the body cannot be a two legged walking robot, with rotating head and the ability to walk around in a building.

It is the case that understanding neural activity, in terms of brain functioning, becomes more difficult as the culture size increases. With a 3 dimensional structure, monitoring activity deep within the central area, as with a human brain, becomes extremely complex, even with needle-like electrodes. In fact the present 100,000 neuron cultures are already far too complex at present for us to gain an overall insight. When they are grown to sizes such as 30 million neurons and beyond, clearly the problem is significantly magnified.

Looking a few years out, it seems quite realistic to assume that such cultures will become larger, potentially growing into sizes of billions of neurons. On top of this, the nature of the neurons may be diversified. At present rat neurons are generally employed in studies. However human neurons are also being cultured even now, thereby bringing about a robot with a human neuron brain. If this brain then consists of billions of neurons, many social and ethical questions will need to be asked [4].

For example - If the robot brain has roughly the same number of human neurons as a typical human brain then could/should the resultant living entity in which the brain resides have similar rights to humans? Also - What if such creatures have far more human neurons than in a typical human brain – e.g. 100 billion times more – would they make all future decisions rather than regular humans? Certainly the restrictions in size which result from the limitations of residing in a human body are no longer apparent. It means that as we look to the future we will no doubt witness thinking robots with brains not too dissimilar to those of humans.

Braingate Implant

It is the case that many human brain-computer interfaces are used for therapeutic purposes, in order to overcome a medical or neurological problem. A good example of this is the use of implants for deep brain stimulation in order to overcome the effects of Parkinson's Disease. We will look at this further in the next section. The possibilities of 'Human Enhancement' are not really considered!

With more general brain-computer interfaces the therapy - enhancement situation is complex. In some cases it is possible for those who have suffered an amputation or who have a spinal injury due to an accident, to regain control of devices via their (still functioning) neural signals [5]. Meanwhile stroke patients can be given limited control of their surroundings, as indeed so can those who have such as motor neurone disease.

With these cases the situation is not straightforward, because on top of any restorative aspects, each individual is usually given abilities that no normal human has – for example the ability to move a cursor around on a computer screen from neural signals alone [6].

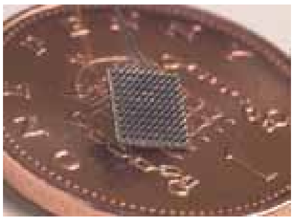

Figure 3: A 100 electrode, 4X4mm Microelectrode Array, shown on a UK 1 pence piece for scale

Some of the most impressive human research to date has been carried out using the microelectrode array, shown in Figure. 3. The individual electrodes are 1.5mm long and taper to a tip diameter of less than 90 microns. Although a number of trials not using humans as a test subject have occurred, human tests are at present limited to two groups of studies. In the second of these the array has been employed in a recording only role, most notably recently as part of (what is called) the 'Braingate' system.

Electrical activity from a few neurons monitored by the array electrodes was decoded into a signal to direct cursor movement. This enabled an individual to position a cursor on a computer screen, using neural signals for control combined with visual feedback. The same technique was later employed to allow the individual recipient, who was paralysed, to operate a robot arm [7]. The first use of the microelectrode array (shown in Figure 3) has though considerably broader implications which extend the capabilities of the human recipient.

As a step towards a more broader concept of brain--computer interaction and as an initial look at the possibilities of human enhancement, the microelectrode array (shown in Figure 3) was implanted into the median nerve fibers of a healthy human individual (the author) during two hours of neurosurgery in order to test bidirectional functionality in a series of experiments. Stimulation current applied directly into the nervous system allowed information to be sent to the user, while control signals were decoded from neural activity in the region of the electrodes [8]. In this way a number of trials were successful [9].

1. Extra sensory (ultrasonic) input was successfully implemented (see Figure 4 for the experimentation).

2. Extended control of a robotic hand across the internet was achieved, with feedback from the robotic fingertips being sent back as neural stimulation to give a sense of force being applied to an object (this was achieved between Columbia University, New York (USA) and Reading University, England).

3. A primitive form of telegraphic communication was brought about directly between the nervous systems of two humans (the author's wife assisted) [9].

4. A wheelchair was successfully driven around by means of neural signals.

5. The colour of jewellery was changed as a result of neural signals – also the behavior of a collection of small robots.

Perhaps in all of the above cases it could be argued that the trial proved useful for purely therapeutic reasons, e.g. the ultrasonic sense could be useful for an individual who is blind or the telegraphic communication could be very useful for those with certain forms of Motor Neurone Disease.

Figure 4: Experimenting with an ultrasonic sense.

Each trial can however also be seen as a form of human enhancement beyond the human norm for an individual. Indeed the author did not need to have the implant for medical purposes to overcome a problem but rather the experimentation was performed purely for scientific exploration. The question arises therefore as to how far should things be taken? Clearly enhancement by means of Brain-Computer Interfaces opens up all sorts of new technological and intellectual opportunities, however it also throws up a raft of different ethical considerations that need to be addressed directly.

When ongoing experiments of the type described involve healthy individuals where there is no reparative element in the use of a brain computer interface, but rather the main purpose of the implant is to enhance an individual's abilities, it is difficult to regard the operation as being for therapeutic purposes. Indeed the author, in carrying out such experimentation, specifically wished to investigate actual, practical enhancement possibilities [8 - 11].

It is clear, from the experiments, that extra sensory input is one practical possibility that has been successfully trialled, however improving memory, thinking in many dimensions and communication by thought alone are other distinct potential, yet realistic, benefits, with the latter of these also having been investigated to an extent. To put it bluntly – all these things appear to be possible (from a technical viewpoint at least) for humans in general.

As we look to the future it is quite possible that commercial influences coupled with the societal wishes to communicate more effectively and perceive the world in a richer form will drive a market desire with regard to such implants. Ultimately direct brain to brain communication, possibly using implants of the type described, is a very exciting proposition, possibly resulting in thoughts, emotions, feelings, colours and basic ideas being transmitted directly from brain to brain. Whilst this raises many questions as to how it would work in practice, clearly we would be foolish not to push ahead to try to achieve it.

Deep Brain Stimulation

The number of Parkinson's disease (PD) patients is estimated to be 120-180 out of every 100,000 people, although the percentage is increasing rapidly as life expectancies increase. For decades researchers have exerted considerable effort to understand more about the disease and to find methods to successfully limit its symptoms [12], which are most commonly periodic (and frequently acute) muscle tremor and/or rigidity. Many other symptoms such as haunched stooping may however occur in later stages of PD.

In the early stages of PD, the drug levodopa (L-dopa) has been the most common form of treatment since 1970. However the effectiveness of L-dopa decreases as the disease worsens and for many patients the severity of side effects increases, something that is more apparent when the onset of the disease occurs at a younger age.

Surgical treatment, such as lesioning used to be an alternative when drug treatments become ineffective. Lesioning can alleviate symptoms thus reducing the need for drug therapy all together. Indeed this is still performed to some extent. However a further alternative treatment of PD by means of Deep Brain Stimulation (DBS) became possible when the relevant electrode technology became available from the late-1980s onwards. From then on, many neurosurgeons have moved to implanting neurostimulators connected to deep brain electrodes positioned in the thalamus, sub-thalamus or globus pallidus for the treatment of PD symptoms such as tremor, dystonia and pain.

A Deep Brain Stimulation device contains an electrode lead with four or six cylindrical electrodes at equally spaced depths attached to an implanted pulse generator (IPG), which is surgically positioned in the body cavities at the top of the chest. In fact DBS has many advantages in comparison with the alternatives such as being reversible. It is also potentially much less dangerous than lesioning and is, in many cases, highly effective.

However, on the down side it presently utilizes a continuous relatively high amplitude current simulation at high frequency (typically 150-180 Hz.) resulting in the need for regular battery replacement every 24 months or so. The cost of battery replacement, the time-consuming surgery involved and the trauma of the repetitive surgery required severely limits the patients who can benefit, particularly those who are frail, have problems with their immune system or are not particularly wealthy.

The obvious solution, namely remote inductive battery recharging is fraught with problems such as the size of passive coil size that needs to be implanted, nasty chemical discharges that occur within the body and perhaps worst of all the 'wasted' time that a patient must remain in an awkwardly fixed position next to a charging station – even then the mean time between replacements is only marginally improved. Another solution to prolong the battery life is simply to improve battery technology. However, the link between price of battery and battery life is clear. If we are considering a battery that could potentially supply the stimulation currents required over a ten or twenty year period then the technology to achieve this in a low cost, implantable, durable form is nowhere near being on the horizon.

Ongoing research involving the author is aimed at developing an 'intelligent' stimulator [13-16]. The idea of the stimulator is to produce warning signals before the tremor starts so that the stimulator only needs to generate signals occasionally instead of continuously – thereby operating in a similar fashion to a heart pacemaker.

Artificial Intelligence (AI) tools such as Artificial Neural Networks [13] have been shown to successfully provide tremor onset prediction. Data input to the network is provided by the measured electrical Local Field Potentials obtained by means of the same deep brain electrodes used for stimulation, i.e. the electrodes are employed in a bidirectional fashion. The network is trained to recognise the nature of electrical activity deep in the human brain and to predict (several seconds ahead) any subsequent tremor onset. In this way the DBS device is 'intelligent', the aim being to only trigger the stimulation by means of the AI system.

Many issues exist with the AI system as much pre-processing of the neural data is necessary along with frequency filtering to minimize the difficulty of prediction. Comparative studies are now ongoing to ascertain which AI method appears to be the most reliable and accurate in a practical situation [16].

False positive predictions (the AI system indicating that a tremor is going to occur when in fact this is not the case) are not really a problem. The end result in such situations is merely that the stimulating current would be applied when it is not strictly necessary. In any event no actual tremor would occur, which is a good outcome for the patient, however unnecessary energy would have been used. That said, results show that the network can be readily tuned to avoid the occurrence of most false positives anyway.

Missing the prediction of a tremor onset is though extremely critical and is not acceptable. Such an event would mean that the stimulating current would not come into effect in time, if at all, and the patient would actually suffer from tremors occurring for a period at least.

Intelligent deep brain stimulators are starting to be designed [14, 15]. In such a case a computer (artificial brain) is used to understand the workings of specific aspects of the human brain. The job of the artificial brain is to monitor the normal functioning of the human brain so that it can accurately predict a negative event, such as a Parkinson tremor, several seconds before it actually occurs. In other words the artificial brain's job is to out think the human brain and to stop it doing what it 'normally' wants to do. Clearly the potential for this system to be applied for a broad spectrum of different uses is enormous.

Non-Invasive Brain-Computer Interfaces

By far the most studied Brain-Computer Interface to date is that involving Electroencephalography (EEG) and this is due to a number of reasons. Firstly it is non-invasive, hence there is no need for surgery with potential infection or side effects. Ethical approval requirements are therefore significantly less and, due to the ease of electrode availability and their simple compatibility, costs are relatively low.

It is also a portable procedure, involving electrodes which are merely stuck on to the outside of a person's head and can be set up in a lab with relatively little training and little background knowledge and taking little time.

The number of electrodes actually employed for experimental purposes can vary from a small number, say 4 to 6, to what is perhaps the most commonly encountered 26-30, to well over 100 for those attempting to achieve a higher resolution. It may be that individual electrodes are attached at specific locations or a cap is worn in which the electrodes are pre-positioned. The care and management of the electrodes also varies considerably between experiments from those in which the electrodes are positioned dry and external to hair to those in which hair is shaved off and gels are used to improve the contact made.

In some cases a study is more for medical purposes, one example being to investigate the onset of Epileptic seizures in patients, however the range of applications is widespread. The most typical and/or interesting are included briefly here to give an idea of possibilities and ongoing work rather than for a complete overview of the present state of play.

Typical are those in which subjects learn to operate a computer cursor in this fashion [17]. However, even after significant periods of training (many months), the process is slow and usually requires several attempts before limited success is achieved. Along much the same lines, numerous research groups have used EEG recordings to switch on lights or control a small robotic vehicle and control other analogue signals [18, 19]. A similar method was employed, with a 64-electrode skull cap, to enable a quadriplegic to learn to carry out simple hand movement tasks by means of stimulation through embedded nerve controllers [20].

It is also possible to consider the uniqueness of specific EEG signals in response to associated stimuli and to use this as an identification tool [21]. Meanwhile interesting results have been achieved using EEG for the identification of intended finger taps, whether the taps occurred or not, with high accuracy. This is useful as a fast interface method as well as a possible prosthetic tool [22, 23].

EEG experimentation is relatively cheap, portable and easy to set up, however it is still difficult to see its widespread use in the future. It has a role to play in externally assessing some aspects of brain functioning for medical purposes, e.g. assessment of epileptic seizures and neural activity during Obsessive Compulsive Disorder, and surely these applications will increase in due course. But the possibility of people driving cars whilst wearing a cap of electrodes, with no need for a steering wheel, is not thought (by the author) to be realistic.

Subdermal Magnetic Implants

Research using subdermal magnetic implants [24] involves the stimulation of mechanoreceptors by an implanted permanent magnet manipulated through an external electromagnet. Permanent magnets retain their magnetic strength over a very long period of time and are robust to various conditions. Hard ferrite, Neodymium and Alnico are easily available, low cost permanent magnets deemed to be suitable for this.

The implanted magnet is agitated in response to an external magnetic field. The amount of agitation is directly proportional to the externally applied signal. In this way different external sensory signals can be sensed by the implantee through the extent of magnet vibration.

The highest density of mechanoreceptors is found in the fingertips, especially in the index and middle fingers. They are responsive to relatively high frequencies and are extremely sensitive to frequencies in the range 200Hz-300Hz.

The pads of the middle and ring fingers were the preferred sites for experiments involving magnet implantation [24]. A simple interface containing a coil mounted on a wire-frame and wrapped around each finger was designed to generate the magnetic fields to stimulate movement in the magnet within the finger. The general idea is that output from an external sensor is used to control the current in the wrapped coil. So as the signals detected by the external sensor change, these in turn are reflected in the amount of vibration experienced through the implanted magnet.

A number of application areas have been experimented on [24]. The first being ultrasonic range information. Distance information from the ranger was encoded via the ultrasonic sensor as variations in frequency of current pulses, which in turn were passed on to the electromagnetic interface. This allowed a practical means of providing information about the individual's surrounding for navigational assistance. The distances were understood within a few minutes of use.

A further application involves reading Morse signals. This application scenario applies the magnetic interface for communicating text messages using an encoding mechanism suitable for the interface. In this way text input can be encoded and the codes dots and dashes transmitted to the interface. The dots and dashes can be represented as either frequency or magnetic field strength variations.

RFID Implants

The final experiment to be considered briefly here is the implantation of a Radio Frequency Identification Device (RFID) (see Figure 5) as an indication of identity. Such a device transmits a sequence of pulses by radio and these represent a unique number. The number can be pre-programmed to act like a PIN number on a credit card. So, with an implant of this type, when activated, the code can be checked by computer and the identity of the carrier specified.

Such implants are being used to gain access to night clubs in Barcelona and Rotterdam (The Baja Beach Club), as a high security device by the Mexican Government and as a medical information source (having been approved in 2004 by the U.S. Food and Drug Administration which regulates medical devices in the USA). In the latter case, information on an individual's medication, for conditions such as diabetes, is stored in the implant. As it is implanted, details cannot be forgotten, the record cannot be lost, and it will not be easily stolen.

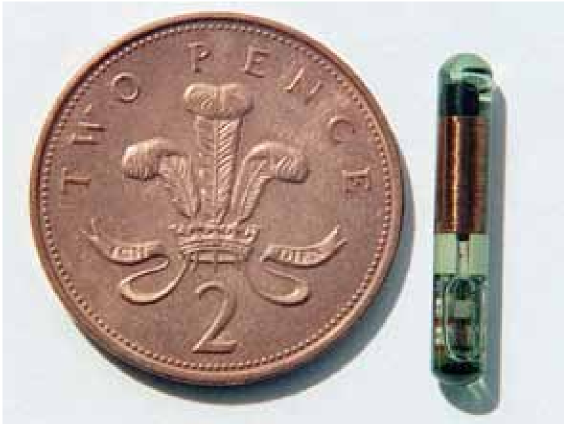

Figure 5: RFID Implant next to a UK 2 pence coin.

The implant does not have its own battery. It has a tiny antenna and microchip enclosed in a silicon or glass capsule. The antenna picks up power remotely when passed near to a larger coil of wire which carries an electric current. The power picked up by the antenna in the implant is employed to transmit by radio the particular signal encoded in the microchip. Because there is no battery, or any moving parts, the implant requires no maintenance.

The first such RFID implant to be put in place in human occurred on 24 August 1998 in Reading, England. It measured 22 mm by 4 mm diameter. The body selected was the author of this article. The implant allowed the author to control lights, open doors and be welcomed "Hello" when he entered the front door at Reading University. Such an implant could be used in humans for a variety of identity purposes – e.g. as a credit card, as a car key or (as is already the case with some other animals) a passport.

To this time there have been many recipients of RFID implants and all echo the sentiments of cochlear implant and heart pacemaker users - the implant quickly becomes perceived as being part of the body and what the user understands to be their body. In essence, the boundaries between human and machine become theoretical. Clearly the separation between humans and technology is rapidly diminishing.

Conclusions

In this chapter a look has been taken at several different implants. Experimental cases have been reported to indicate how humans or animals can merge with technology in this way.

When considering robots with biological brains, clearly such an approach allows for 'complete body engineering' in which brain size, body size, power, communications and other abilities are optimized for the requirements in hand. It may well be that the human body is not best suited to the technological world in which it now operates and hence we see problems such as obesity as a direct consequence. Maybe this technique will ultimately open up a future route for human development whereby humans can cast off the shackles and limitations imposed by the restrictions of having to live in a biological body.

In the section on the Braingate implant a look was taken at the potential for human enhancement. Already extra-sensory input has been achieved, extending the nervous system over the internet and a basic form of thought communication. So it is likely that many humans will upgrade and become part machine themselves. This may of course mean that ordinary humans are left behind as a result.

Then came a section on deep brain stimulators employed chiefly to counteract the effects of Parkinson's Disease. This was followed by a look at standard EEG electrodes which are positioned externally and which therefore are encountered much more frequently. Unfortunately the resolution of such electrodes is relatively poor and they are only useful for monitoring and not stimulation. We may well be able to use them to learn a little more about how the brain operates but it is difficult to see them being used for highly sensitive control operations.

Finally we considered subdermal magnetic implants and their use for sensory substitution, enabling humans to extend their range of sensory input. This was followed by a brief look at RFID implants for identification purposes. Overall the range of methods considered here has therefore been quite broad. The common theme being the forming of a human-technology merged system, potentially which benefits from the advantages of both. Both for therapy and ultimately enhancement, this would clearly appear to be the future for humanity.

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