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ORIGINAL PAPER

The Cyborg Revolution

Kevin Warwick

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Abstract This paper looks at some of the different practical cyborgs that are realistically possible now. It firstly describes the technical basis for such cyborgs then discusses the results from experiments in terms of their meaning, possible applications and ethical implications. An attempt has been made to cover a wide variety of possibilities. Human implantation and the merger of biology and technology are important factors here. The article is not intended to be seen as the final word on these issues, but rather to give an initial overview. Most of the experiments described are drawn from the author's personal experience over the last 15 years.

Keywords Cyborgs · Enhancement · Embodiment · Prosthetics · Therapy

Introduction

For many people, the term 'cyborg' (meaning cybernetic organism—part biology, part technology) is associated solely with science fiction and, in particular, films such as *The Terminator*, *Blade Runner* or *Minority Report*. In fact, a wide variety of practical cyborgs exist today in the real world, and these new entities raise ethical questions about where they might lead and the impacts they might have on society at large [21]. However, each specific cyborg has a different emphasis depending on the types of technology and connection it involves. In the case of bio-machine hybrids, in particular, the ethical questions that arise depend very much on the kind of hybrid investigated. Each methodology therefore needs to be thought about in turn.

This paper looks at several different experiments that have linked biology and technology together in a cybernetic fashion, ultimately combining biology and machines in a cyborg merger. What is crucial to this is that it is the overall final system that is important. Where a brain is involved, which surely it is, it must be seen not as a stand-alone entity, but as a fully embedded, integral component of the overall system—that adapts to the system's needs [2]. The overall combined cybernetic creature is the system of importance, although the brain's role as a controlling interest is arguably the most significant aspect.

The paper is arranged so that experiments are described in turn in individual sections. While there are distinct overlaps between the sections, they all throw up unique considerations. Following a description of each investigation, pertinent aspects of the topic are discussed. Points have been raised with a view to near-term-future technical advances and what these might mean in a practical scenario. No attempt is made here to present a conclusive account of the field; rather, the

K. Warwick (✉)
Coventry University,
Priory Street, Coventry CV1 5FB, UK
e-mail: k.warwick@reading.ac.uk

aim has been to highlight the range of research that is being carried out, see what is actually involved in the work that is being done and look at some of its implications. In each case, the technical description is followed by a brief discussion of some of its philosophical spin-offs and societal impacts.

Many of the experiments described here in fact represent personal experiences made by the author and his colleagues and co-workers over the last 15 years. Others who have worked with the author on the experimentation described include neurosurgeons, medical doctors, pharmacists, engineers, computer scientists and philosophers. Essentially, each of the experiments is described with a relatively brief overview, which builds on other publications that are cited in the list of references and may be consulted for more in-depth information. As a result, what can be gleaned from this article is an individual perspective based on practical experience and experimental results.

Biological Brains in a Robot Body

Neurons cultured/grown under laboratory conditions on an array of non-invasive electrodes provide an attractive alternative to computer or human control with which to construct a robot controller. An experimental control platform, essentially a robot body, can move around within a defined area purely under the control of such a network/brain, and the effects of the brain, controlling the body, can be observed [29]. Of course, this is interesting from a robotics perspective, but it also opens up a different approach to the study of the development of the brain itself because of its sensory motor embodiment. This method allows investigations to be carried out into memory formation and reward/punishment scenarios—the elements that underpin the basic functioning of a brain. It also makes intriguing contributions to the debate about cyborgs [23].

In most cases, the growth of networks of brain cells (typically around 100,000 at present) in vitro firstly involves separating neurons obtained from foetal rodent cortical tissue. They are then grown (cultured) in a specialised chamber, where they can be provided with suitable environmental conditions (e.g. kept at an appropriate temperature), and fed with a mixture of minerals and nutrients. An array of electrodes embedded in the base of the chamber (a multi-electrode array, MEA) acts as a bidirectional electrical interface to/from the culture. This allows electrical signals to be delivered in order to stimulate the culture and also recordings to be made of the outputs from the culture [25].

The neurons in such cultures spontaneously connect, communicate and develop, giving useful responses within a few weeks and typically continuing to do so for, at present, 3 months. The brain is grown in a glass specimen chamber lined with a flat '8 × 8' multi-electrode array, which can be used for real-time recordings (see Fig. 1). This makes it possible to distinguish the firings of small groups of neurons by monitoring the output signals on the electrodes. A picture of the entire network's global activity can be formed in this way. It is also possible to electrically stimulate the culture via any of the electrodes to induce neural activity. In consequence, the multi-electrode array forms a bidirectional interface with the cultured neurons [1, 4].

The brain can then be coupled to its physical robot body [29]. Sensory data fed back from the robot are subsequently delivered to the culture, thereby closing the robot-culture loop. In consequence, the processing of signals can be broken down into two discrete 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 the robot sensor to stimulate the culture [24, 25].

The actual number of neurons in a brain depends on natural density variations that arise when the culture is seeded 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 as input by the culture, thereby closing the loop [24, 25].

Once the brain has grown on the array for several days, during which time it forms some elementary neural connections, an existing neuronal pathway through the culture is identified by searching for strong relationships between pairs of electrodes. These 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 [24, 25].

A rough input–output response map of the culture can then be created by cycling through the electrodes in turn. In this way, a suitable input/output electrode pair can be chosen in order to provide an initial decision-

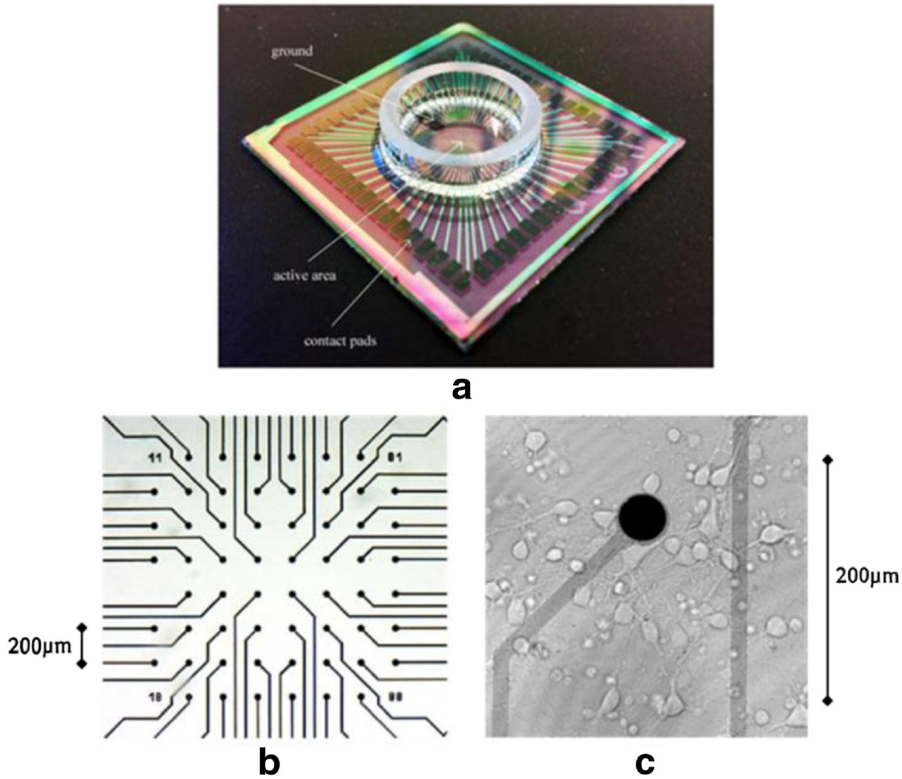

Fig. 1 **a** A multi-electrode array (MEA) showing the electrodes. **b** Electrodes in the centre of the MEA seen under an optical microscope. **c** An MEA at ×40 magnification, showing neuronal cells in close proximity to an electrode

making pathway for the robot. 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 an object that is located ultrasonically (possibly a wall) in order to keep moving [24].

For experimental purposes, the intention is for the robot to follow a forward path until it reaches a wall, at which point the front sonar value decreases below a certain threshold, triggering a stimulating pulse. If the responding/output electrode registers activity, the robot turns to avoid the wall. In experiments, the robot turns spontaneously whenever activity is registered on the response electrode. The most relevant result is the occurrence of the chain of events: wall detection–stimulation–response. From a neurological perspective, of course, it is also interesting to speculate why there is activity on the response electrode when no stimulating pulse has been applied [25].

As an overall control element for direction and wall avoidance, the cultured brain acts as the sole decision-making entity within the feedback loop. Clearly, the neural pathway changes that take place over time in the culture between the stimulating and recording electrodes are then an important aspect of the system. From a research point of view, investigations of learning and memory are generally at an early stage. However, the robot can be clearly 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 habitually performing these activities—an example of learning due to habit [10].

However, the number of variables involved is considerable, and the plasticity process, which occurs over quite a period of time, is (most probably) dependant 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 currently a major issue for research in this field [25].

'On many occasions the culture responds as expected, on other occasions it does not, and in some cases it provides a motor signal when it is not expected to do so' [22]. But does it 'intentionally' make a different decision to the one we would have expected? We cannot tell, but merely guess. When it comes to robotics, it has been shown by this research that a robot can successfully have a biological brain with which to make its 'decisions'. The size of such a brain, 100,000–150,000 neurons, is dictated purely by the current limitations on the experimentation described. Three-dimensional structures are already being investigated and will permit the creation of cultures of approximately 30 million neurons [25].

The potential of such systems, including the range of tasks they can deal with, means that the physical body can take on different forms. There is no reason, for example, why the body could not be a two-legged, walking robot, with a rotating head and the ability to walk around in a building. It is realistic to assume that such cultures will become larger, potentially growing to 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 now, thus raising the possibility of 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 [20, 30], especially regarding the rights of such creatures.

One interesting question is whether or not such a brain is, or could be, conscious. Some (e.g. [18]) have concluded that consciousness is an emergent property; essentially, it is sufficient to put enough human neurons together with a high degree of connectivity, and consciousness will emerge. In the light of this argument, there is therefore no immediate reason why robots with biological brains composed of sufficient numbers of human neurons should not be conscious. The possibility of building a robot with a technological body and a brain that consists of a large number of highly connected human neurons is not far off. Should this be perfectly acceptable or should it be regulated? If a robot of this kind decided to commit a crime, then who would be responsible for the consequences, the robot itself?

The BrainGate

When we specifically consider the case of cyborgs, it is clear that most practical experimentation involves human subjects, often self-experimenters of one type or another, being linked closely with some form of technology. Although many human brain–computer interfaces are used for therapeutic purposes in order to overcome a medical/neurological problem, one example being deep brain stimulation electrodes employed to overcome the effects of Parkinson's disease [16, 31], the possibility of enhancement is an enticing prospect for cyborgs.

However, the therapy/enhancement question is not a simple one. In some cases, those who have suffered an amputation or received a spinal injury in an accident are able 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 can people with conditions such as motor neurone disease [23, 25].

The situation is not straightforward in these cases, as each individual is given abilities that no normal human possesses, for example, the ability to move a cursor around on a computer screen using neural signals alone [12]. The same quandary is encountered when it comes to blind individuals who benefit from some extra-sensory input, for instance from a sonar system based on the same principle as bat echolocation: it does not repair their blindness, but allows them to rely on an alternative sense [25].

Some interesting human research has been carried out using the microelectrode array known as the Utah Array, or more popularly the BrainGate. The individual electrodes are 1.5 mm long and taper to a tip diameter of less than 90 microns. Although a number of trials have been carried out that did not use humans as test subjects, human tests are limited to two groups of studies at the moment. In the second of these, the array has been employed in a purely recording role.

Essentially, electrical activity from a few neurons monitored by the array electrodes was decoded into a signal that directed cursor movements. This enabled an individual to position a cursor on a computer screen using neural signals for control in combination with visual feedback. The same technique was later deployed to allow the individual recipient, who was paralysed, to operate a robot arm [11]. Nevertheless, the first use of the microelectrode array (shown in Fig. 2) has considerably broader implications for attempts to extend the human recipient's capabilities.

Deriving a reliable command signal from a collection of monitored neural signals is not necessarily a simple task, partly due to the complexity of the signals recorded and partly due to the real-time constraints on the

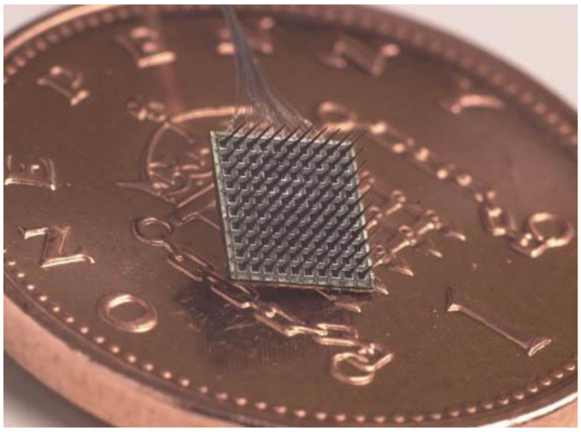

Fig. 2 A 100-electrode, 4×4 mm microelectrode array, shown on a UK one-pence piece for scale

handling of the data. In some cases, however, it can be relatively easy to look for and obtain a system response to certain anticipated neural signals, especially when an individual has trained extensively with the system. In fact, the neural signal's shape, magnitude and waveform over time are considerably different to other apparent signals, such as noise, and this makes the problem a little easier to resolve [25].

The interface through which a user interacts with technology provides a layer of separation between what the user wants the machine to do and what the machine actually does. This separation imposes a cognitive load on the individual concerned that is proportional to the difficulties experienced. The main problem is interfacing the human motor and sensory channels with the technology in a reliable, durable, effective, bidirectional design. One solution is to avoid this sensorimotor bottleneck altogether by interfacing directly with the human nervous system [23].

An individual human connected in this way can potentially benefit from some of the advantages of machine/artificial intelligence such as rapid and highly accurate mathematical abilities of great use in 'number crunching', a high-speed, almost infinite, Internet knowledge base, and accurate long-term memory. In addition to this, it is widely acknowledged that humans have only five senses that we know of, whereas machines offer modes of perception that exploit infrared, ultraviolet and ultrasonic signals, to name but a few [25].

Humans are also limited in that they can only visualise and understand the world around them in three dimensions, whereas computers are quite capable of dealing with hundreds of dimensions. Perhaps most importantly, human means of communication, essentially transferring a complex electrochemical signal from one brain to another via an intermediate, often mechanical, slow and error-prone medium (e.g. speech), are extremely poor, particularly lacking in speed, power and precision. It is evident that, over the long term, using an implant to connect a human brain to a computer network could open up the distinct advantages of machine intelligence, communication and sensing abilities to the implanted individual [24].

As a step towards a broader concept of brain–computer interaction, a microelectrode array (like the one shown in Fig. 2) was implanted into the median nerve fibres of a healthy human individual (the author) in the course of 2 h 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 [27]. A number of trials were undertaken successfully using this setup [28].

In particular [24, 25],

1. Extra-sensory (ultrasonic) input was successfully implemented
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 directly between the nervous systems of two humans (the author's wife assisted) was performed [28].
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 behaviour of a collection of small robots.

In most, if not all, of the above cases, the trial could be described as useful for purely therapeutic reasons, e.g. the ultrasonic sensory input might be of use to an individual who is blind, while telegraphic communication might be beneficial to people with certain forms of motor neurone disease. Each trial can, however, also be seen as a potential form of enhancement beyond the human norm for an individual. Indeed, the author did not need to have the implant for medical reasons in order to overcome a problem; rather, the experimentation was carried out purely for the purposes of scientific exploration. It is therefore necessary to consider how far things should be taken.

Clearly, enhancement with the aid of brain–computer interfaces introduces all sorts of new technological and intellectual opportunities, but it also throws up a raft of different ethical concerns that need to be addressed directly [19]. While the vast majority of people are perfectly happy for interfaces of this kind to be used in therapy, it can be argued the picture is not as clear when it comes to enhancement. But what about individual freedom? If someone wants to stick a pin in their nose or finger, that is a matter for them. Should the situation be any different if they want to stick 100 pins in their brain, even if it endows them with additional abilities?

Therapy

It is an open question whether or not a bio-technology link that is created purely for therapeutic reasons constitutes a cyborg. I do not intend to embark upon such a wide-ranging discussion here. It is merely worthwhile mentioning one particular example, primarily because of the future opportunities that it opens up. An alternative treatment for Parkinson's Disease using deep brain stimulation (DBS) started to be feasible when the relevant electrode technology became available from the late 1980s onwards. Since then, many neurosurgeons have started implanting neurostimulators connected to deep brain electrodes positioned in the thalamus, subthalamus or *globus pallidus* of the brain to treat tremors, 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 below the collar bone. DBS has many advantages, such as the fact that it is reversible. It is also potentially much less dangerous than lesioning, and is highly successful in many cases [24].

Ongoing research is aimed at developing an 'intelligent' stimulator [31]. The idea of the stimulator is to produce warning signals before the tremors begin so that the stimulator only needs to generate signals occasionally rather than continuously, thus operating in a similar fashion to a heart pacemaker. Artificial intelligence (AI) tools based on artificial neural networks have been shown to successfully predict the onset of tremors [23]. In either case, data input into a network is provided by the measured electrical local field potentials obtained by means of the deep brain electrodes. The network is trained to recognise the nature of electrical activity deep in the human brain and to predict (several seconds ahead) the subsequent outcome, i.e. the onset of tremors. In consequence, the DBS device becomes 'intelligent' when the stimulation is triggered solely by the AI system.

While deep brain implants like those described are aimed primarily at providing current stimulation for therapeutic purposes, they can also have a broader portfolio of effects within the human brain. In the case of 'intelligent' stimulators, a computer (artificial brain) is used to understand the workings of specific aspects of the human brain. The job of the artificial brain, as can be seen from the description of the experimentation, is to monitor the normal functioning of the human brain so that the artificial brain can accurately predict a spurious event, such as a Parkinson tremor, several seconds before it actually occurs. In other words, the artificial brain's job is to outthink the human brain and stop it from doing what it 'normally' wants to do [23].

One practical issue at the present time is that the deep brain electrodes can be connected bidirectionally with a computer. Furthermore, it is quite possible for the computer to be located remotely. Hence, signals within the brain can be tracked in real time and fed into a computer. The computer is able to analyse these signals and generate alternative signals that are fed directly back into the brain in order to ensure the person in question continues to function.

Another good example in this section on therapy is the work of Todd Kuiken [13]. The first beneficiary of his technique was Jesse Sullivan, hailed in the media as the world's first 'Bionic Man', who lost both of his arms as a result of an accident he sustained during his work as a high-power electrical lineman. At the Rehabilitation Institute of Chicago, his arms were replaced with robotic prosthetics that he was able to control merely by thinking about using his original arms in the normal way.

The method involved taking nerves that originally ran to Sullivan's arm and reconnecting them to muscles in his chest. When he thought about lifting an arm, for example, muscles in his chest contracted instead of muscles in the original arm. Electrodes connected externally between the chest muscles and the robotic arm caused the prosthetic replacement to interpret such contractions as instructions to move in a particular way.

Evidently, the technology described in this section has enormous potential for application in a broad spectrum of different fields. Restricting this technology to therapeutic purposes would also limit the need for philosophical argument. At the same time, extending the scope for its application would open up numerous possibilities. In itself, employing such methods to make individuals happy (by overcoming depression) draws attention to the possibility of recreational uses. Perhaps the most significant option would potentially be their use to overcome negative character traits, and not merely bad habits, a scenario fictionalised in *The Terminal Man* [3]. If signals could then be transmitted remotely from a brain to a computer and back again, who would be responsible for that person's actions, particularly if they were to commit a crime?

Body Modification

The final category to be considered is something of a catch-all for the discussion of various other procedures that have not been covered above. The first idea to be considered is the use of implant technology, the implantation of a radio frequency identification device (RFID) as a token of identity, for example. In its simplest form, such a device transmits by radio a sequence of pulses that represent a unique number. The number can be preprogrammed to function rather like a PIN number on a credit card. If someone has had an implant of this type inserted and activated, the code can be checked by computer and the identity of the carrier determined.

Such implants have been used as a sort of fashion item, to gain access to night clubs in Barcelona and Rotterdam (The Baja Beach Club), as a high security device for the Mexican Government or as a source of medical information (having been approved in 2004 by the US Food and Drug Administration, which regulates medical devices in the USA; see [7, 6]). In the latter case, information about the medication an individual requires for conditions such as diabetes can be stored on the implant. Because it is implanted, the details cannot be forgotten, the record cannot be lost, and it will not easily be stolen.

An RFID implant does not have its own battery. It incorporates a tiny antenna and a microchip enclosed in a silicon or glass capsule. The antenna picks up power remotely when it passes close to a larger coil of wire that carries an electric current. The power picked up by the antenna in the implant is employed to transmit the particular signal encoded on the microchip by radio. Because there is no battery and it does not contain any moving parts, the implant requires no maintenance whatsoever; once it has been implanted, it can be left in place [24].

A RFID implant of this kind was put in place in a human for the first time on 24 August 1998 at Reading, England. It measured 22 mm long with a 4-mm diameter cylinder. The body (arm) selected was that of the author of this paper. The doctor who carried out the procedure (George Boulos) burrowed a hole in the upper left arm, pushed the implant into the hole and closed the incision with a couple of stitches.

The main reason for selecting the upper left arm for the implant was that we were not sure how well it would work. We reasoned that, if the implant was not working, it could be waved around until a stronger signal was transmitted. It is interesting that most present day RFID implants in humans are located in a roughly similar place (the left arm or hand), even though they do not have to be. Even in the James Bond film *Casino Royale* (the 2006 remake), Bond himself has an implant in his left arm [24].

The RFID implant allowed the author to control lights, open doors and be welcomed with a 'Hello' whenever he entered the front door of Reading University [26]. An implant of this kind could be used in humans for a variety of identification purposes, e.g. as a credit card, a car key or (as is already the case with some other animals) a passport or at least a passport supplement.

The use of implant technology to monitor people opens up a considerable range of issues. It is now realistic to talk of tracking individuals by means of implants or, alternatively, for more widespread application and coverage, the Global Positioning System, a wide area network or even a mobile telephone network. From an ethical point of view, though, it raises considerable questions when it is children, the elderly (e.g. those with dementia) or prisoners who are subjected to tracking, even though this might be deemed to be beneficial for some people [26].

The use of implants to track people is still at the research stage. As such devices come onto the market, there will be numerous (special) cases with distinct drivers. For example, there would have to be a potential gain for a person to be tracked and their position monitored in this way, especially if it could be deemed to either save or considerably enhance their life—as possibly in the case of an individual with dementia [23].

Another intriguing piece of cyborg technology is described in the work of Neil Harbisson. This was originally referred to as the 'Eyeborg' project. The technology developed involved a head-mounted sensor that translates colour frequencies into sound frequencies [17]. Initially, Harbisson memorised the frequencies related to each colour, but subsequently he decided to permanently attach the eyeborg to his head, effectively meaning a small camera faces forward from over his forehead and is connected to the back of his skull by a metal bar. Eventually, the eyeborg was developed further so that Harbisson was able to perceive colour saturation as well as colour hues. Software was then developed that enabled Harbisson to perceive up to 360 different hues through microtones and saturation through different volume levels [9].

Coincidentally, another project referred to as the 'Eyeborg' project has been carried out by documentary maker Rob Spence, who replaced one of his eyes with an eyeball-shaped video camera. The prosthetic eye contains a wireless transmitter that sends real-time colour video to a remote display. Spence lost his original right eye when playing with a gun on his grandfather's farm at the age of 13. He therefore decided to build a miniature camera that could be fitted inside his false eye. Spence refers to himself as 'the Eyeborg guy'.

The video camera runs on a 3-V battery. It should be emphasised that the camera is not connected to his optic nerve and has not restored his vision in any way. Instead, it is used to record what is in his line of sight remotely on a computer. The current model is low resolution, and the transmitter is weak, meaning that a receiving antenna has to be held against his cheek to get a good signal. A better-performance, higher-resolution model, complete with a stronger transmitter and an improved receiver, is apparently under development.

In 2009, a computer programmer called Jerry Jalava lost part of the fourth finger on his left hand in a motorcycle accident. Rather than merely leave a gap or replace it with a cosmetic finger copy, the part-finger was replaced with a 2-GB USB stick. It is felt this is worth mentioning in view of the examples discussed below.

One final area to be considered is that of subdermal magnetic implants [8]. This involves the controlled stimulation of mechanoreceptors by an implanted magnet manipulated through an external electromagnetic coil. Clearly, issues such as magnetic field strength sensitivity and frequency sensitivity are important. Implantation is an invasive procedure, which makes implant durability an important requirement. Only permanent magnets retain their magnetic strength over a very long period of time and are robust enough to survive a range of testing conditions. This restricts the type of magnet that can be considered for implantation to permanent magnets. Hard ferrite, neodymium and alnico magnets are easily available, inexpensive and suitable for this purpose.

The magnetic strength of the implant magnet contributes to the amount of agitation the implant magnet undergoes in response to an external magnetic field and also determines the strength of the field that is present around the implant location. The skin on the human hand contains a large number of low threshold mechanoreceptors that allow humans to experience in great detail the shape, size and texture of objects in the physical world through touch. The highest density of mechanoreceptors is found in the fingertips, especially those of the index and middle fingers. They are responsive to relatively high frequencies and are most sensitive to frequencies in the 200–300-Hz range.

The pads of the middle and ring fingers were the preferred sites for magnet implantation in the experiments that have been reported [8]. A simple interface containing a coil mounted on a wire frame and wrapped around each finger was designed for the generation of the magnetic fields that would stimulate movement in the magnet within the finger. The general idea was that the output from an external sensor would be used to control the current in the wrapped coil. As the signals detected by the external sensor changed, they were reflected in the amount of vibration experienced through the implanted magnet [24].

Experiments have already been carried out in a number of areas of application [8]. The first was ultrasonic range information. This scenario connected the magnetic interface to an ultrasonic ranger for navigation assistance. Distance information from the ranger was encoded via the ultrasonic sensor as variations in the frequency of current pulses, which were passed on to the electromagnetic interface in turn. It was found that this mechanism constituted a practical means of supplying reasonably accurate information about the individual's surroundings and so providing navigational assistance.

The distances were understood intuitively after a few minutes of use, and their perception was enhanced by distance 'calibration' through touch and sight [24].

A further application involved reading Morse signals. This application scenario used the magnetic interface to communicate text messages to humans using an appropriate encoding mechanism. Morse code was chosen to encode the messages on account of its comparative simplicity and for ease of implementation. It was possible for text input to be encoded as Morse Code and the dots and dashes transmitted to the interface. The dots and dashes were represented by variations in either frequency or magnetic field strength.

From an ethical perspective, the implants considered in this section are perhaps easier to evaluate, possibly because they are more open to social assimilation. Yet, interestingly, apart from Neil Harbisson's colour Eyeborg, they are generally not intended for therapeutic purposes, but to enhance the carrier's capacities in some way. At this stage, however, they do not appear to openly threaten the fabric of society and merely modify the human body in ways that are, some may feel, not too different from someone wearing jewellery. Furthermore, it is difficult to imagine further extensions along the same lines bringing about major cultural or scientific shifts or modifying our thinking or behaviour.

Conclusions

This paper has looked at several different kinds of cyborg. Experimental cases have been discussed in order to indicate how humans can merge with technology in this way, thereby throwing up a plethora of social and ethical questions. In each case, the practical experimentation that actually took place has been described, rather than a merely theoretical concept. It is worth acknowledging here that there are numerous other types of interface. For instance, use can be made of non-invasive EEG electrodes. It was felt that these examples would not add sufficient variety to the ensuing discussion, and they were consequently not covered here for reasons of space.

In particular, if robots are to have biological brains, this could ultimately mean some form of human brain operating in a robot body. Would it be deemed cruelty to robots if a brain of this type were to be 'switched off'? More importantly at the present time, it is necessary to ask whether such research should be permitted to forge ahead regardless. Before too long, we may well have robots with brains made up of human neurons that possess the same sorts of capabilities as the human brain [24].

The BrainGate implant offered an opportunity to consider the potential for human enhancement. Extra-sensory input has already been achieved scientifically, extending the nervous system over the Internet and creating a basic form of thought communication. It is likely that many humans will wish to upgrade and become part-machine themselves. This may mean that ordinary (non-implanted) humans will be left behind as a result.

Ethical issues relating to the particular experiments discussed have been explored superficially in each case. However, one feature common to all these projects is that they fuzzify the difference between what is regarded as an individual human and what is regarded as a machine.

Personal Comments

Apart from therapeutic applications, the current concept of cyborg technology and experimentation does not fit snugly into an established research profile. In consequence, funding bodies are not easily persuaded to provide support for such experiments. Nonetheless, research done by the author on the creation of a robot with a biological brain was supported with £0.5 million of funding over a 3-year period by the UK Engineering and Physical Sciences Research Council, so such support is not completely out of the question. Irrespective of this, the experiments undertaken by Graafstra, Harbisson, Spence, Jalava and others have certainly not been conducted within the scientific mainstream. However, this has often been the case with novel scientific research in the past.

Quite a few people have now tried an implant of one type or another, especially RFID and magnetic implants. For the most part, this has been done outside the medical–scientific system and often with artistic intentions. One problem with this is the difficulty it causes for those who wish to gather accurate information about the results obtained from these individuals' activities. Such information often has to be gleaned and translated from web pages rather than being extracted from the traditional academic journals in which authors have to comply with conventions for the presentation of data.

On the whole, many aesthetic and artistic approaches to techno-body modification in this vein are refreshing from a scientific perspective as well and can sometimes arrive at interesting results and give ideas to those with scientific training. When these activities approach what seems a form of self-mutilation, however, it may be felt things have been taken a little further than is necessary in order to fulfil the originator's artistic ambitions. There is an exciting range of technology available to us today, technology that was simply inconceivable in the past, and this opens up possibilities for experimentation. However, experiments need to be conducted in an appropriate, ethical fashion if they are to be welcomed warmly by the scientific community.

As regards the non-mainstream cyborg experiments discussed in the section on body modification, these might loosely be categorised as experiments that [1] are artistic or aesthetic, [2] expand human perception, or [3] enhance or augment the human body. They touch on many different issues such as self-mutilation, scientific usefulness, respectability and personal freedom. Certainly, each has different ethical implications. For example, an experiment carried out purely by an individual is a very personal matter, whereas the reputation of the institution would also be at stake, along with any insurance commitments, if the same experiment were to be conducted within a company or university. Where a larger institution is concerned, it might also be felt that the organisation was somehow promoting the experiment as though it was a good thing.

Body modification experiments are certainly on the increase as the technology becomes more widely available and the perceived dangers are accordingly felt to be small. At the same time, there are increasing numbers of personnel with the skills to carry out implantation procedures. There is therefore no reason why such modifications could not become a widespread sociocultural phenomenon such as tattooing and piercing today. They will though, I feel, require solid justifications, such as practical or artistic objectives, if they are to be more than mere gimmicks.

There will definitely be those who comment negatively on such experimentation, perhaps saying that it adds nothing to technical or scientific progress, but it is merely frivolous and does little apart from feed good stories to the media. Despite this, it is necessary for decision-makers to realise that, firstly, there are many therapeutic possibilities, secondly, the whole field of human enhancement needs to be investigated rigorously and scientifically and, thirdly, it could easily be more life-enhancing than any other technological change on the agenda today. It should also be remembered that if we have learned anything from history, it is that just about every new technological change attracts a certain amount of criticism. The bigger the change, the greater the number of critics.

The cyborg experiments described in this paper could well be the first practical steps towards a coming merger of humans and machines in the techno-evolutionary sense of the ideas put forward by futurologists like Ray Kurzweil [14]. However, the actual implants used and technologies ultimately settled on may well change along the way. Again and again, history has shown this is to be very much the norm.

According to a recent survey in the USA [15], 53 % of Americans think it would be a change for the worse if most people wore implants or other devices that constantly showed them information about the world around them. Considering that the vast majority of people have very little concept of the implants that are available and what they can do, this is already a very low figure. As implants become more widespread, we can expect this figure to diminish. It will, in consequence, not take long for those who share such concerns to be in the minority.

In the near future, cyborgs based on existing technologies and technologies that are currently in the pipeline will probably be little different from humans. Apart, that is, from the odd extra sense or communication skill. However, as the technology and interfacing improve, will this mean the abilities possessed by cyborgs eventually change the rules and fabric of social life? The big question will be what happens to ordinary humans, those who are not part-machine. Will they still have a substantial role to play?

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