Institution: University of Reading

Unit of Assessment: 13 Electronic and Electrical Engineering

Title of case study: Interfacing brains with machines: public engagement and potential to benefit human health and quality of life

1. Summary of the impact

The Cybernetics team at the University of Reading works at the frontier of human-machine interaction. The group carries out research on therapy and human enhancement in collaboration with medical professionals, to research new therapeutic treatments for patients with paralysis. Our work has led to the first human implantation of BrainGate, an intelligent deep brain stimulator, and the culturing of neurons within a robot body. Our work has been used by neurosurgeons in experimental human trials with the aim to enhance the standard of living of paralysed individuals. This ground breaking, and sometimes controversial work, has sparked widespread discussion and debate in the public sphere, within the media and at the government level, on the use of machines to enhance humans and vice versa.

2. Underpinning research

The BrainGate is a 100-electrode implant developed by Cyberkinetics, Inc. (originally a Brown University spin-off) that links the nervous system to a computer network, enabling the nervous system to be stimulated externally. The Reading team used this implant, together with technology developed at the Unit [1] (operational system, signal processing, communications), to achieve the first human implant of BrainGate. The implant was fired into the median nerves of Professor Warwick's left arm on March 14th 2002 in a 2 hour operation. The implant was connected to a processing unit to allow stimulation of nerve fibers to artificially generate sensation perceivable by the subject and recording of local nerve activity to form control commands for wirelessly connected devices.

During evaluation of the implant system the nervous system of Professor Warwick was connected onto the internet in Columbia University, New York, enabling a robot arm in the University of Reading to use Professor Warwick' neural signals to mimic his hand movements, while allowing him to perceive what the robot touched from sensors in the robot's finger tips [2]. Further studies also demonstrated that it was possible to communicate directly between the nervous systems of two individuals, the first direct and purely electronic communication between the nervous systems of two humans

Further research, from 2004 to present, with MRC support, used an artificial intelligence system connected to the brain via deep embedded electrodes to accurately predict the onset of Parkinsonian tremors up to 20 seconds in advance [3,4]. The electrodes were then used to provide deep brain stimulation to counteract these tremors before they took hold. This is in direct contrast to traditional deep brain stimulation techniques where a continuous stimulation signal is used to control tremors and therefore this research is opening up other possible routes to treatment.

Finally, from 2007 to present, with various EPSRC listed support, we cultured a population of approximately 100,000 to 150,000 living neuronal cells (rat and human) on a multi-electrode array within a closed loop robot body. In this novel set-up the cultured brain cells were connected within a robot body [5]. The robot's sensory readings were used to stimulate the cell culture and the cell activity was then in turn used to change the robot's behaviour - for example, to control its movement inside a small corral. The work demonstrated that cultures of neurons can be used to

control a robot to avoid obstacles, thereby creating a platform for investigating culture plasticity (the capacity for neural pathways to change due to feedback) [6].
These experiments have led to a basic reassessment of how the brain and nervous system operate. The work could lead to new therapies to directly help those with a disability or neurodegenerative disease such as Parkinson's. The work reveals the tantalising, but for some, provocative, possibility of being able to change and possibly enhance the basic functioning of a brain by linking it directly with technology.

The research was led by Professor Kevin Warwick who joined the University as Professor of Cybernetics in 1988. Professor Nasuto (Reader in Cybernetics since 2000, becoming Professor in 2012) and Dr Mark Gasson (research staff since 2004) formed part of the team developing this technology. Dr Ben Whalley joined the department of Pharmacy in 2005 and has collaborated with Professor Warrick's team on the biomedical aspect of this research.
Other external biomedical collaborators include consultant neurosurgeons Tipu Aziz, Peter Teddy and Amjad Shad at the John Radcliffe Hospital, Oxford, UK.

3. References to the research

Key publications:

1. *M. Gasson *et al.,* "Invasive Neural Prosthesis for Neural Signal Detection and Nerve Stimulation", *Int. J. Adaptive Control & Signal Processing*, **19**, 365-375, (2005).
2. *K. Warwick *et al*., "The Application of Implant Technology for Cybernetic Systems", *Archives of Neurology* **60**, 1369–1373 (2003).
3. *D. Wu *et al., "*Prediction of Parkinson's Disease Tremor Onset using Radial Basis Function Neural Network Based on Particle Swarm Optimization", *International Journal of Neural Systems* **20**, 109–118 (2010).
4. J. Burgess *et al.*, "Identifying Tremor-Related Characteristics of Basal Ganglia Nuclei During Movement in the Parkinsonian Patient", *Parkinsonism & Related Disorders,* **16**, 671-675, (2010).
5. K. Warwick *et al*., "Controlling a Mobile Robot with a Biological Brain*", Defence Science Journal*, **60**, 5-14, (2010).
6. D. Xydas *et al., "*Revealing ensemble state transition patterns in multi-electrode neuronal recordings using hidden Markov models", *IEEE Transactions on Neural Systems & Rehabilitation Engineering* **19**, 345–355 (2011).

The research has been published in high quality peer-reviewed journals and has been internally assessed as of at least 2* quality. Those suggested for quality assessment as indicated with *.

Key grants:

K. Warwick, S. Nasuto and V. Becerra, "Investigating the computational capacity of cultured neuronal networks", *EPSRC*, 2007–2010, £491,000.
K. Warwick, "Toward the prediction of Parkinson Disease tremor for a demand-driven deep brain stimulator", *MRC*, 2007, £67,409.
S. J. Nasuto (jointly with University of Plymouth), "Brain-computer interface for monitoring and inducing affective states", *EPSRC*, 2011–2016, £1,150M (University of Reading share £614,000).
S. J. Nasuto (jointly with Goldsmiths College), "Cognition as communication and interaction", *Sir John Templeton Foundation*, 2011–2013, £120,000 (University of Reading share £60,000).

S. J. Nasuto, “NeuroCloud: developing a hybrid cloud architecture for neuroscience research”, *EPSRC*, 2010–2012, £250,000 (co-investigator)
S. J Nasuto, “Towards an integrated neural field computational model of the brain”, *EPSRC*, 2010, £248,000 (co-investigator grant).
S. J. Nasuto, “Bridging the gaps initiative, complex cognitive science”, *EPSRC*, 2007–2010, £556,000 (co-investigator grant).

4. Details of the impact

Impact on ethical discussions and public engagement

This research has garnered considerable public interest through magazine articles, radio and television pieces (international news, discussion and documentaries), e.g. cover story on Wired Magazine http://www.wired.com/wired/archive/8.02/warwick.html, Late Night with Conan O’Brien (NBC), Ideas that Changed the World (BBC)[6] in 2010, YouTube clips, blogs and Wikipedia discussions. Warwick has been featured in multiple radio and news outlets, and popular science television programmes discussing this research, e.g. Museum of Curiosity on Radio 4 in 2013. The work has been presented at various prestigious lectures, e,g. IET Pinkerton Lecture in 2012 World Science Festival in New York City 2009, schools, TEDx talks, e.g. University of Chicago in 2011, University of Warwick in 2012, and through invited talks at medical, philosophical and technical conferences. An exhibition in London’s Science Museum was devoted to the work using cultured neurons in a robotic machine, and was in place for 18 months from 2008. The Science Museum maintains a website specifically dedicated to our research[7], a resource used by schools and colleges as an integral part of their course structure. The research also featured in the 2012 Wellcome Trust (London) “Superhuman” exhibition, http://www.wellcomecollection.org/press/press-releases/superhuman.aspx, which was visited by nearly 80,000 people[1]. The work has been subject to many schools projects and presentations globally, some under the auspices of the Royal Society via its Acclaim project, others due to local organisation. In 2011, Google selected the implant research as a major source of inspiration for young scientists. The work was used as one of only five examples in the world for the Google Science Fair[8]. The collaboration with Dr Ben Whalley integrating cultured neurons into a robot body appeared as a story and video in New Scientist[2]. The two versions of the video have collectively been viewed over 2.5 million times[9]. The work was also included in the Faraday Schools programme[13] in 2013.

Impact on human health and quality of life

As a direct consequence of the first successful BrainGate implant in a human, studies have subsequently been performed to assist individuals who are paralysed to considerably enhance their quality of life[4,12]. The research carried out at Reading showed that the concept of technological integration with the human nervous system was possible, the Unit pioneered the first direct human neural control of a robotic arm, its success and lack of adverse effects contributed to the obtaining of ethical approval for further implantations of the BrainGate system[4]. The subsequent use of BrainGate has improved patient outcomes, as demonstrated in human trials reported in Nature in 2012[12]. BrainGate has enabled paralysed individuals to control technology around them directly from their neural signals. Research on the use of BrainGate has now moved on to a formal human clinical trial (trial identifier: www.clinicaltrials.gov/ct2/show/NCT00912041). In 2013 the Director of the Neurorehabilitation Engineering Center at the University Medical Center

Gottingen, NL used a similar approach for prosthesis control by neural signals and specifically referred to Reading's work in his design[11].
In 2009 the Director of the Alfred Mann Institute for Biomedical Eng., USA, integrated Reading's research with biocompatible tech and specifically referred back to the Unit's work[10]
Research into the intelligent deep brain stimulator is on going[2] although in a Mail on Sunday article of 2008 the design of an intelligent on demand stimulator by the team was hailed as "the most significant recent advance in biomedical engineering"[14].

Impact on government awareness of technology developments and their implications

In (2010)The Danish Council of Ethics used the Unit's research to question the ethical aspects of cyborg technology, leading to the release of a suite of recommendations http://bit.ly/1e7tO4d
At the UK government's Future Horizon Scanning Meeting in 2009, the University of Reading team was specifically involved[5] in developing the government's stance on national security. This included issues such as identity, neural control and communication as considered in our research. As a consequence the Reading team is also involved in the planning and presentation of the forward looking "Cross-Government Futures Symposium" to be held in Feb 2014. The Symposium is designed to consider differing views and perspectives about the future and what they will mean for UK Government strategy and policy beyond the next Parliamentary term[5].
In terms of these issues the group's direct, practical work across the spectrum of neural implants and growing brains, as described here, is of direct relevance in shaping future Government policy.

5. Sources to corroborate the impact

1. Curator of Temporary Exhibitions at the Wellcome Trust, London (*)
2. Senior Technology Correspondent, New Scientist (*)
3. Consultant Neurosurgeon at the John Radcliffe Hospital, Oxford and Professor of Neurosurgery at Oxford University - Parkinson's Disease applications (*)
4. Vascular and Critical Care Neurologist at Massachusetts General Hospital, Boston and Visiting Associate Professor of Neurology at Harvard University – BrainGate (*)
5. Defence Science and Technology Laboratory, Horizon Scanning Team Leader (*)
6. http://www.imdb.com/title/tt1791025/
7. http://www.sciencemuseum.org.uk/antenna/ratbrains/
8. http://www.youtube.com/watch?v=-lqNO3hij_E
9. http://www.youtube.com/watch?v=1-0eZytv6Qk
10. J. Schulman, "Brain Control and Sensing of Artificial Limbs", in Biological & Medical Physics, pp. 275-291, Springer, 2009.
11. D. Farina et. al., "Controlling Prostheses using PNS Invasive Interfaces for Amputees", Chapter in Introduction to Neural Engineering for Motor Rehabilitation, Wiley, 2013.
12. L. Hochberg et al., "Reach and Grasp by people with Tetraplegia using a Neurally Controlled Robotic Arm", Nature, 485, pp.372-375, 2012.
13. http://www.faradayschools.com/site-map/events/
14. https://sites.google.com/site/lmssonline/lmss-blog/professorkevinwarrick13thjanuary2011

(*) Contact details provided separately as per guidance