Disability and Technology

Engineering a More Equitable Ireland

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Many of the practical difficulties faced by people with disabilities can be addressed through development, provision, and promotion of assistive technology. Engineers who are not directly involved in the disability sector should be aware that by designing devices, environments, and amenities so that they are accessible to people with the widest range of abilities, they can promote greater equality of opportunity in education, employment, and citizenship for disabled people.

Engineering academia plays a part in increasing societal equality for people with disabilities. For example, over a period of 20 years the engineering research laboratory in Ireland's National Rehabilitation Hospital has hosted approximately 150 disability-related research projects at undergraduate, postgraduate, and postdoctoral levels. The primary benefit of disability-related projects in engineering education is often portrayed as technological outcomes. Unfortunately, only a small minority of such projects translate directly into actual innovative assistive technology products that become widely available to the people who can benefit. More frequently, projects

Digital Object Identifier 10.1109/MTS.2010.935975

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contribute to future developments indirectly through academic publication. In the experience of those involved in this laboratory, an important benefit of the majority of these projects has been the lasting impact on the student engineers who undertook them, giving them a better understanding of the humanitarian role of engineering.

Humanitarian Engineering in Action

People with disabilities tend to be marginalized in many societies, frequently being prevented from accessing public services and amenities, or being deprived of the opportunity to work despite the availability of jobs to which they are well suited. The right to education and employment, which is enshrined in the United Nation's (UN's) Universal Declaration of Human Rights, is denied to many people because they have a disability. Through discrimination, ignorance or practical hindrance, many are even prevented from expressing themselves freely. In some of the world's most prosperous nations, assistive technology that could facilitate a reasonable level of independence for people with disabilities is simply not available to them. Engineers have the means to create a more level playing field, a society in which people with disabilities can participate fully, as they are entitled to do. By developing and providing appropriate technology and by promoting inclusive designs of devices, environments and services, engineers can help to build a more inclusive society.

Rehabilitation engineering and assistive technology research are good examples of humanitarian engineering in action. These areas provide an ideal opportunity for students in higher education to take on projects that have real importance, not only because of the potential for the technology produced to improve quality of life, but also because of the educational benefit and sense of professional responsibility that it gives to the students. While those who undertake such projects gain interdisciplinary experience and potentially contribute to the increased independence of people with disabilities, the experience also often has a profound personal impact on the students. When students involved in these projects recognize that engineering can have a positive impact on the lives of those who are disadvantaged or socially excluded, the students gain a sense of professional responsibility and compassion.

Disability and Design

Disability is often perceived as something "wrong" with a person. This viewpoint sees "disability" as stemming from a medical diagnosis and is often referred to as the *medical model*. While this perspective seems intuitively valid to many people, it is not palatable to all. In particular, many people (including many groups working with or representing people with disabilities) favor the *social model* of disability. This proposes that disability is primarily defined not by a person's medical condition, but by the prejudices and exclusionary practices of society. Inclusive design of devices, amenities, and environments can ameliorate many of the practical difficulties encountered in daily life. In the same way that the widespread availability of spectacles allows the majority of vision impairments to be perceived as minor inconveniences rather than a disability, a widespread appreciation among designers and engineers of accessible design could substantially offset the negative impact of disability. Encouraging students to appreciate the significance of the social model of disability can be a challenge for engineering academics teaching in disability-related subjects.

One concept that provides useful practical guidance to engineers is that of Universal Design (UD), which refers to the design of objects or environments so that they are accessible to, or usable by, people with the widest range of abilities. A defining principle of UD is that access be provided to users with different abilities without segregation or stigma. In other words, objects or environments should wherever possible be accessed in an identical way by users with different abilities. Where this is impossible or impractical, equivalent access should be provided to all users. UD, which comprises seven separate principles [1], can form the basis of enlightening design projects for engineering students. Designing in accordance with these seven principles encourages students to reflect on the significance of the social model of disability and to appreciate the opportunity engineers have to accomplish positive change in society.

The problems associated with many disabilities cannot realistically be solved simply through careful design of the objects and environments with which everyone (able-bodied and disabled) interacts.

Rather, many people rely on dedicated assistive technology devices for mobility, independence, or communication (e.g. wheelchairs, prosthetics, hearing aids, speech synthesizers, and computer input devices). Rehabilitation engineers are involved in developing new assistive technology devices and refining existing ones.

National Rehabilitation Hospital Laboratory in Dublin

University College Dublin's Rehabilitation Engineering Laboratory, situated within Ireland's National Rehabilitation Hospital (NRH), was established as part of the University's Department of Electronic and Electrical Engineering in 1986 by Professor Annraoi de Paor, who remained its Director from that time until his retirement in 2005. During those years, each of the other authors worked for a period in what has become a nationally influential center for research into disability-related technology. The laboratory was originally founded at the request of Dr. Tom Gregg, who was then medical director of the NRH. He saw that engineering could be used in countless ways to enhance the independence and quality of life of people with disabilities, but that the necessary facilities were not available to the staff or patients of the hospital at that time. The laboratory was established to fulfill that need.

During Professor de Paor's tenure, the laboratory hosted numerous research projects – approximately 100 Bachelor's degree projects, 40 Master's projects, and 10 Ph.D.s – most of which arose directly through interaction with the patients and therapists in the hospital. The laboratory was also opened to other institutions, and several students registered at Dublin Institute of Technology and at the University of Dublin worked there. A few of the laboratory's projects are described below.

Accessible Reading Machine

One of the early projects undertaken was the development of a reading aid. This project arose through consultation with a quadriplegic patient who identified without hesitation what he most missed due to his disability – the ability to read a book. At that time, many reading aids were available, which sought by pneumatic or purely mechanical means to mimic the action of the hand in turning the pages of a book. However, this patient's experience of these devices had been very frustrating – they would frequently tear or crease pages or turn two at once. None of them allowed the user to refer back to an earlier page. As a result, using these devices had required such frequent intervention from a care-giver that he had ultimately abandoned them altogether. Having verified the patient's account of the reading aids in question, the lab's engineers and technicians embarked upon a new design that reached fruition in a project done by a final year undergraduate engineer, Linda Hickey.

The new design, based upon the ancient principle of scrolling, requires that the book be dismantled and its pages pasted onto a roll of acetate, such as those used on many overhead projectors. For a typically sized novel, four pages appear at once in a visual frame. The rollers are mounted in a motorized frame. One motor gives forward scrolling, one reverse, and the third turns the entire frame 180° about a vertical axis, to allow the reverse sides of the pages to be read. In the original design, the machine was controlled using sip and puff switches. A short puff of air into a mouthpiece advanced the pages by one visual frame, registration in the center of the field of view being effected by breaking an infrared beam by a strip of opaque tape to the side of the book's pages on the edge of the roll of acetate; a long puff turned the pages back by one visual frame; and a sip caused vertical rotation. (See Fig. 1.)

Fig. 1. A switch-operated scrolling reading machine, shown under the control of a sip-and-puff switch.

Since its creation, the scrolling reading machine has instigated several more projects to implement alternative user interfaces for it, including a single-switch scanning radio-controller and a sound-activated controller that recognizes common speech sounds. The latter interface has the advantage of being non-contact and therefore has eliminated the risk of cross-infection between patients who shared the machine while resident in the hospital.

Although many books are now available electronically, which facilitates reading through a computer under the control of an accessible interface device, the scrolling reading machine still remains in constant use today. Its ability to provide independent access to any book, provided that the pages are prepared on a scroll, is difficult to replicate electronically. Without any special

Fig. 2. An adapter box that allows an electric applicance to be controlled using a switch. These devices are used by Occupational Therapists for people with head injuries who are re-learning to associate cause and effect.

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training, a person can prepare such a scroll quite rapidly and it does not require the cooperation of the publisher or any specialized equipment. Furthermore, many readers find it less tiring to their eyes to read from paper rather than from an electronic screen. The original machine has now been donated to a girl born without limbs, who uses it to read her school books.

The design of the reading machine resulted in a patent and the technology was licensed to a manufacturer of specialized rolling beds for paralyzed people, but it did not subsequently become available as a product. Unfortunately, this experience is not unusual in the area of assistive technology where products are highly specialized. Even when an innovative assistive technology addresses a clearly articulated need, unless the potential market is large enough to persuade a manufacturer to turn the solution into a product, it remains unavailable to potential users.

Switches in Rehabilitation

Many projects undertaken in the NRH lab have been carried out in cooperation with the staff of the hospital, and almost all have originated as requests or suggestions from staff. One of the themes that has arisen repeatedly over the years, particularly in interaction with the hospital's occupational therapists and speech and language therapists, has been the use of switches in rehabilitation to control assistive technology programs and devices. In this context, the term switch can refer to any device that allows a user to generate an on-off signal, whether it is an actual mechanical switch (e.g., a button) or some kind of sensor that recognizes a repeatable voluntary gesture and translates it into a binary signal. A switch provides the most basic fallback mechanism for device accessibility since it represents the simplest possible communication channel between the user and a device.

Switches are widely used in rehabilitation as a last line of communication for people with severe disabilities. In some cases, communication through conventional means such as speech, writing, or typing is impossible due to a person's disability. In such cases, provided that at least one gesture or physiological parameter remains under some degree of voluntary control, communication may yet be facilitated by means of a single switch. First, an appropriate switch that can reliably detect the person's voluntary action must be identified. Using such a switch, simple communication can be established, for example using "yes" or "no" questions or by calling out the letters of the alphabet in sequence for the person to select one at a time, spelling out a message.

Using an automatic scanning menu system, a person who might otherwise be unable to communicate can be provided with a channel of expression. Furthermore, by interfacing such a system with an environmental control device, the person can be placed in control of their surroundings (e.g., appliances in the home or workplace), facilitating a greater degree of independence. Careful and intelligent organization of a scanning, switch-accessible menu system maximizes the user's communication rate. Other enhancements such as a predictive text feature can further optimize communication.

One of the switch-related projects carried out in the NRH lab involved the construction of custom-designed electronic switch interface boxes for the hospital's Occupational Therapy department where they are now used in retraining head-injured people in the operation of associating cause and effect. The interface box allows any electrical appliance such as a radio to be powered on or off using any simple switch. Controls on the box allow it to be configured in one of three action modes:

- Momentary mode, in which the appliance is powered only as long as the switch is depressed,
- Latched mode, in which the appliance is toggled on or off each time the switch is pressed, and
- Timed mode, in which the appliance stays on for a user-selectable period of time after each press of the switch.

By way of illustration, we recall one case in which the interface box in timed mode proved remarkably effective. A patient had suffered a head injury and was proving unresponsive to any stimulus. Prior to his injury, he had been a keen music fan, so the interface box was set up to facilitate control of a tape recording of some of his favorite music using a switch. One of the therapists demonstrated repeatedly to him that by pressing the switch, he would be rewarded with a short burst of music. Eventually, he made a tentative movement towards the switch and later actually pressed it. When the music stopped he touched the switch again, and at length learned to press it in the right cadence to get continuous playing. He then began to engage with the Occupational Therapists in the rehabilitation program designed to re-form pathways in the brain to take over, when possible, some of the functions of damaged areas.

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Facilitating Communication by Profoundly Physically Disabled People

Occasionally, engineers in the laboratory receive requests from therapists in the hospital to design custom devices for patients with profound physical disabilities for whom no suitable commercially available system can be found. In such cases, it is generally desired that some vestigial movement which remains under the person's voluntary control – the twitch of a finger for example, or slight deflection of the eyes – can be detected automatically so that it can serve as a channel of communication and control through which the person can interact with the wide range of switch-accessible assistive technology devices commercially available.

One of the most successful projects to have begun in this way concerned the development of a webcam-based system for the detection of eye blinks in a patient otherwise completely paralyzed. The camera is trained on the user's face and a continuous analysis of the color distribution is made in real-time. This distribution is quite different depending on whether the eyes are open or closed. When a deliberate and sustained blink is detected, a software switch is closed, which controls the action of a scanning keyboard on the screen. This system was also interfaced to the patient's CD player so that he could control it in a similar manner. The use of low-cost consumer hardware in this project adhered to a principle that has been central to many of the laboratory's projects – to identify solutions that can be implemented in an affordable way or even as free software. This system was made available to other users for a time but, due to the lack of resources to maintain and update a software application like this as hardware and operating systems evolve, it is no longer available. However, the novel image processing algorithm on which it was based was published internationally for others to use [2].

In some cases, even though a paralyzed person retains a degree of control over some body movement, it proves difficult to identify a mechanical switch that can be operated consistently. This can be because the movement that remains under voluntary control is not consistent, varying in strength from day to day or with the person's level of fatigue. On one occasion a person might not be able to muster the strength to press a button that requires a robust push, but on another might experience involuntary twitches or spasms that make a more sensitive button unusable due to accidental triggering. Another problem that can arise is that certain movements can only voluntarily be initiated in one direction so that, for example, a person might be able to press a button with finger but be unable to withdraw that finger to release the button. Without a therapist or care giver to assist the person in returning their finger to the primed position, the button cannot be used repeatedly.

To address these problems, engineers in the laboratory designed an electromechanical switch simulator that could reproduce the feel and action of a variety of mechanical buttons. Furthermore, it could exhibit behavior not possible with a passive mechanical switch, such as an exaggerated restorative force that drives the switch back to the open position once a press is detected, overcoming the problem of a user who cannot voluntarily withdraw their finger. The prototype was constructed by a final year undergraduate project student, Niamh Connolly, who integrated the device with real-time simulation software running on a PC via an analog input/output card so that different switch profiles could easily be loaded on the simulator [3].

As part of another project, to facilitate creative expression by children with physical disabilities, a system was developed that allows drawings to be created using vocalizations alone [6]. Another prototype system allows each of a number of appliances in the home to be assigned a unique sequence of musical notes (i.e., a tune). Each appliance can then be switched on or off simply by singing or whistling its tune or playing notes on a set of "pipes of Pan." Similarly, a system was created that allows the computer mouse pointer to be controlled using variations in musical pitch [7].

Based on a proposal by an undergraduate student and kayak enthusiast, Catherine Halpin, a project was undertaken in cooperation with the hospital's Physiotherapy department and the Spinal Injuries Action Group to explore kayaking action as a therapeutic exercise for paraplegic people. A prototype electrically controlled kayaking

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machine was developed, which for the first time allows a wheelchair user to undergo a simulated kayak workout while remaining seated. The machine was a great success with patients in the hospital where it remains in daily use. It was subsequently augmented with a computer simulation of an actual kayak scene in which the user competes against a virtual opponent [8].

In many cases, the application of electrical engineering skills in the humanitarian pursuit of assistive technology solutions has given rise to insights into the underlying processes at work in the human body. For example, investigation of the electrical activity in the brain for the purpose of facilitating communication by paralyzed people gave rise to a completely new universal model of the EEG based on Lyapunov Stability Theory and Chaos Theory [9]. Similarly, the development of a novel system for controlling a computer using eye movements [10], based on the electrooculogram, led to a new mathematical model of the eye movement control system [11]. In a further project, James Condron, as part of his Ph.D. research, applied mathematical and signal processing techniques to investigate autonomic nervous system activity in a biofeedback environment [12].

Role of Academic Research in Rehabilitation Engineering

Student research projects often provide an opportunity to explore an assistive technology concept that might be considered too speculative to pursue in a purely commercial environment. Only a small minority of these projects produce something so compelling that it crosses the threshold to become a commercial product. More frequently, public dissemination of knowledge outcomes from the project, while not immediately placing a solution in the hands of end users, may bring that objective a step closer.

Many exciting and original projects have been undertaken in the NRH laboratory over the last two decades, and many of these have led to successful innovations. Several of these produced devices that remain in use today and others resulted in open publication of research findings. However, the most consistent positive outcome has been the influence on the student engineers carrying out the research. The following are some of the main benefits of student projects in assistive technology:

- Assistive technology projects provide students with an opportunity to reflect on the role of engineers in building a more equitable society.
- A student project can provide a good context in which an unproven idea can be explored in detail. In a minority of cases, this will lead to groundbreaking innovation that would be unlikely to occur in commercially-driven research.
- Assistive technology projects provide students with an opportunity to tackle real-world problems which, although not necessarily commercially attractive, are definitely worth solving.
- These projects provide an excellent opportunity for students to work in a challenging interdisciplinary environment.

Socially Engaged, Technically Challenging Projects

This article has described a selection of rehabilitation engineering projects, spanning a wide range of technologies and disabilities. The intention of presenting these projects is to illustrate that socially engaged, but technically challenging projects can be undertaken by engineering students both at the undergraduate and postgraduate level.

The technology produced can, in fortunate cases, directly benefit people with disabilities in a substantial way. This is often portrayed as the motivation for initiating student projects in this area. However, it is actually unusual for projects of this type to result directly in a piece of technology that can be used by a large number of end users. In twenty years' worth of student projects carried out in the NRH laboratory, a far more common outcome has been that an individual assistive technology user has benefited from the development of a custom device that caters to some very specific need that is not addressed by commercially available devices. For this reason, *direct* benefit to people with disabilities of the technology developed should be acknowledged as only part of the motivation for undertaking these projects.

A more consistent feature of assistive technology research projects is the *indirect* benefit to people with disabilities and to society in general. In addition to the technical experience gained from any substantial student project, assistive technology research provides students with a better understanding of the social implications of engineering. In the case of the NRH laboratory, many of its alumni have gone on to pursue careers in biomedical research. Several are Clinical Engineers in the disability and rehabilitation services, including Ireland's Centre for Excellence in Universal Design. One girl was so taken by the challenge of working with patients that she returned to Medical School after getting Bachelor's and Master's degrees in Engineering, and is now a Medical Doctor in General Practice. Another woman is currently doing a Ph.D. at the Royal College of Surgeons in Ireland. Former project students from the lab occupy senior academic positions in at least half of Ireland's universities and most are actively involved in research in the disability area.

Approximately 150 students carried out Bachelor's, Master's, or PhD research projects in the NRH laboratory during Professor de Paor's tenure as Director. Furthermore, the research community built up around it was deeply involved in the foundation of an interdisciplinary Centre for Disabilities Studies in University College Dublin, which has to date produced well over 100 graduates from Master's and Higher Diploma programs.

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References

[1] B.R. Connell *et al.,* "The principles of universal design," Center for Universal Design at North Carolina State University, 1997; http://www.design.ncsu.edu/cud/pubs_p/docs/poster.pdf

[2] D. Burke, T. Ward, and A. de Paor, "Image processing used to harness blinking as a channel of communication and control for physically disabled people," *Medical & Biological Engineering and Computing*, vol. 39, no. 3, pp. 285–287, May 2001.

[3] N. Connolly, E. Burke, and A. de Paor, "A general purpose electromechanical simulator for switches used in the rehabilitation of communication-impaired people," *Advances in Electrical and Electronic Engineering (Slovakia)*, vol. 3, no. 2, pp. 201–204, May 2004.

[4] Y. Nolan and A. de Paor, "The mechanomyogram as a channel of communication and control for the disabled," in *Proc. IEEE EMBS 26th Ann. Conf.* (San Francisco, CA), Sept. 1-5, 2004, pp. 4928–4931.

[5] G. Pfurtscheller and C. Neuper, "Event-related synchronization of mu rhythm in the EEG over the cortical hand area in man." *Neuroscience Letts.,* vol. 174, no. 1, pp. 93–96, Jun. 6, 1994.

[6] E. Burke, A. de Paor, and G. McDarby, "A vocalisation-based drawing interface for disabled children," *Advances in Electrical and Electronic Engineering (Slovakia),* vol. 3, no. 2, pp. 205–208, May 2004.

[7] E. Burke, Y. Nolan, and A. de Paor, "An investigation into non-verbal sound-based modes of human-to-computer communication with rehabilitation applications," in *Adjunct Proc. HCI Int.* 2003 (Crete, Greece), Jun. 22–27, 2003, pp. 241–242.

[8] C. Halpin and A. de Paor, "An exploration of canoeing action as therapy for spinally injured people," *Advances in Electrical and Electronic Engineering (Slovakia),* vol. 3, no. 2, pp. 296–298, May 2004.

[9] D. Burke and A. de Paor, "A stochastic limit cycle oscillator model of the EEG," *Biological Cybernetics*, vol. 91, no.4, pp. 221–230, 2004.

[10] E. Burke, Y. Nolan, and A. de Paor, "An electrooculogram based system for communication and control using target position variation," in *Proc. IEEE EMBSS UKRI PGBIOMED'05* (Reading, U.K.), Jul. 18–20, 2005, pp. 25–26.

[11] Y. Nolan, E. Burke, C. Boylan, and A. de Paor, "The human eye position control system in a rehabilitation setting," *Advances in Electrical and Electronic Engineering (Slovakia),* vol. 4, no. 3, pp. 118–123, 2005.

[12] J, Condron, "Time-frequency analysis applied to autonomic nervous-system activity in a biofeedback environment," Doctoral thesis, Dublin Institute of Technology, Dublin, Ireland, 2004.