

## Brain-Machine Interfaces: Realm of the Possible

On 28 November 2014, Jan Scheuermann fed herself a bar of chocolate at the University of Pittsburgh Medical Center. For most of us, this would not be a newsworthy event. But for Jan, who is paralyzed from the neck down, it was a major milestone. She was able to command the Modular Prosthetic Limb (MPL) with her thoughts alone to grasp the chocolate bar and feed herself for the first time since becoming paralyzed. The video of the event is beautiful and awe-inspiring not only for its moment of independence and joy but also for the incredible technological achievement that made it possible.<sup>1</sup> Jan is one of the early pioneers of a brain-machine interface (BMI), which is opening new doors for many applications.

Before Jan there was Tim. By controlling an MPL with his thoughts, Tim was able to reach for and touch his girlfriend's hand for the first time since being paralyzed in a motorcycle accident.<sup>2</sup> Beyond the technical accomplishments, both of these demonstrations show the potential for humans to interact with a robot in ways that are very different. The smiles and tears testify to a very human-like connection with the machine.

Mind over matter is now a phrase that is closer than ever, thanks to advances in BMIs. Imagine not being able to move an arm or leg. Even though you can visualize it in your mind, your body is not able to comply. A study by the Christopher and Dana Reeve Foundation found that nearly 1 in 50 people in the United States—almost six million people—are living with some type of paralysis. Leading causes include stroke, spinal cord injury, and multiple sclerosis. For our service men and women, the conflicts in Iraq and Afghanistan have emphasized the potential of these technologies to address combat injuries that result in amputation. Remarkable advances in combat casualty care have resulted in survival rates that surpass any other conflict, and warfighters are surviving severe injuries that often require extensive rehabilitation and support. Often in their early twenties or even still teenagers, these men and women have a lifetime ahead of them, and many want to continue to serve. Beyond the heavy emotional toll on those affected and their caregivers, tens of billions of dollars are spent caring for these individuals every year. But new technologies are bringing new hope, and recent advancements in BMIs demonstrate potential avenues for addressing some of these pressing challenges.

With these challenges in mind, the Defense Advanced Research Projects Agency (DARPA) started the Revolutionizing Prosthetics Program in 2005. The program is an investment in a wide range of neurological and rehabilitative technologies to address the most challenging of these combat-related injuries, and it focused on two objectives. First was the creation of the MPL, the world's most advanced prosthetic arm.<sup>3</sup> The second was to create an interface for the MPL with the human brain so the user could interact with the prosthesis with the same dexterity and feeling as a natural limb and with little conscious thought. To create this interface, small electrodes were placed on the surface of Jan's brain to measure electrical impulses when she thought about moving her arm. Then those signals were decoded and translated into commands to the MPL. Despite the complexity of the technology, to Jan, it was as simple as moving her arm.

Applying these technologies to move a prosthesis is awesome and emotional in reconnecting people with the world. But until recently, that brain-machine connection was one-way—the brain reaching out through the machine, with no feeling or feedback in return. A confluence of technical advances is extending BMIs so that the MPL can communicate back to the brain. Our ability to perceive our environment is as important as—or perhaps even more important than—our ability to move a limb. A major complaint of prosthetic users is the need to look at the prosthesis while using it. Simple tasks like holding a glass and taking a drink with eyes closed are nearly impossible with conventional prostheses. Without a sense of touch and proprioception (knowing where your arm is in space without actually seeing it), simple tasks become extraordinarily difficult. It is a bit like trying to talk after being numbed during a dental appointment. If you cannot feel your mouth, it is difficult to speak clearly. Today, science is beginning to move past this barrier. For example, amputee Johnny Matheny can perceive stimulation of certain nerves as coming from his prosthetic fingers and hand (known as haptic feedback), enabling him to identify objects using sensors located on the fingers of the MPL.<sup>4</sup>

With such potential, BMIs should eventually allow people to communicate with robotics in a more natural, intuitive way. Recent research demonstrates that it may be easier than ever. For example, after Jan spent two years practicing with the arm, we asked the question, "Could she adapt her ability to move the MPL to a very different device?" To

test this, we decided to ask Jan to control an aircraft in a flight simulator. We simply unplugged the MPL and connected a flight simulator that was adapted to convert wrist motions to the motion of a joystick.<sup>5</sup> Although she never had flown a plane, she was able to rapidly achieve level flight and progressed to doing a series of simulated maneuvers and flight patterns, including flying through the Grand Canyon. Amazingly, when asked how she was controlling the aircraft, she told us that, at first, she visualized wrist motions, but she quickly transitioned to just visualizing how she wanted the plane to move, without thinking of her wrist. Furthermore, she described this as one of the most enjoyable experiences she had during the two-year study.

Connecting these individuals with the world, through these machines, is an incredible privilege, and, although the technology is still in its infancy, these applications offer a vision of how we all might be impacted by BMI advances. For decades, the challenge in getting the best synthesis of a human's and a machine's strengths has been the method by which they interact. Take, for example, a specific challenge: texting while driving. It is not that you cannot think of the message that you want to send. It is not that the phone is not perfectly capable of sending the message. The problem is that you must physically interact with the phone—the point of interaction is the problem. Advances in voice recognition help remedy this situation, but not all human-machine interface problems can be solved by voice command. Furthermore, the power of the human mind lies in its ability to process information in parallel, whereas most human-machine interfaces require serial input. If we suddenly need to take evasive action while driving, an experienced driver can assess the situation and implement a course of action almost instantaneously. Now imagine that you had to communicate these instructions by keyboard or voice. Likely a crash would occur before you could communicate your intent.

### **What Else Can Be Done?**

With the promise of BMI technology to solve human-machine interface challenges, the question inevitably arises: What else could be done? How can these advances contribute to national security? Although it might be too soon to begin planning for BMI in everyday life, it is not premature to begin imagining how the technology might be used by the nation. For the military, the first and most obvious application of this technology is to our wounded warrior community. Commercial devices

to restore hearing and sight are already available, and the DEKA Research and Development Corporation's Luke Arm (developed by DARPA) is the most advanced Food and Drug Administration-approved prosthetic arm.<sup>6</sup> While today's applications show great promise, they could go much further. Wearable robotics such as SuitX's Phoenix exoskeleton aim to replace wheelchairs and could integrate BMI.<sup>7</sup> Today's wearable robotics require wearers to use residual capabilities, such as hands and arms, to walk, sit, or stand and are often not intuitive to operate.

Apart from rehabilitation, BMI could also dramatically revolutionize command and control. Thanks in part to the convergence of BMI, that revolution would come with two other technical trends. The first is the proliferation of data and devices used in greater numbers in increasingly complex situations. The second trend is the rapid advancement of artificial intelligence (AI).

For the first trend, we are now able to build more sensors and devices to inform our fighting forces, but the information can easily overcome the ability of the operator to access, analyze, and understand that data—and the machines that contain it. Information critical to mission success can be overlooked because there is so much of it, from weather reports, to radio frequencies, to historical context, to situation awareness. Making the challenge all the more difficult is that, even with all the information, it is difficult to know what to do with it. Furthermore, conflict is increasingly fought in a gray zone, where the distinction between civilian and combatant is (sometimes intentionally) blurry and the actions of one small unit can have broad-reaching or even strategic effects.

For the second trend, the advancement of AI, one of the most interesting research areas today investigates the possibilities of combining the advancements in BMI with advances in AI. Consider, for example, how you hold a coffee cup while having a conversation. To take a drink you must make fine adjustments to keep the cup level, prevent it from slipping, and bring it to your mouth. These actions require complex coordination between multiple muscles, yet you hardly give it a thought. Today's BMIs require conscious control of each action, while much of what we do naturally is a subconscious or learned response. As an example, learning a new task such as swinging a golf club initially requires thinking about how to hold the club, position the shoulder, adjust your stance, and so forth. After many hours of practice you no longer think about these low-level tasks. You concentrate on where you want to hit

the ball to best position yourself for the next shot. Today's BMIs enable individuals to move each joint very naturally but are not capable of capturing the learned response associated with a complex action. This is where AI could excel. Using a BMI, a person could tell the machine what action to perform, and the AI could perform the lower-level functions, freeing the human to concentrate on decision making.

Advances in computing and AI have produced amazing results, but AI still faces fundamental limitations. The best AI systems (like Google's AlphaGo) still require extensive training. They must process information exhaustively, and they cannot generalize knowledge beyond a specific situation. As a result, AI is suboptimal and its application is limited by current technical constraints and policies that restrict its employment. But where AI is deficient today, the human mind excels. They are ideal partners, except for the fact that they do not work well together through the narrow choke point of the human-machine interface. If they could be efficiently coupled, we would have great possibilities for superior decisions and efficient command and control.

### **Technical and Ethical Questions**

While the technical possibilities of BMIs are exciting, there is an important difference between what we *can* build and what we *should* build. That distinction is one that many new technologies confront, and the way that BMI will parse the difference might be similar to how other technologies have done so—especially in genetic engineering and autonomy. But similarities notwithstanding, researchers, operators, and the broader public must think about the implications of developing—or not developing—technologies that interact directly with the brain.

Technically speaking, there are some important hurdles the development community must overcome before this technology can be considered for widespread use or acquisition. First, while BMIs have been demonstrated in multiple applications, we are still far from the sort of fantastic advances we see in Hollywood movies. Take, for example, moving a natural limb, a task that involves hundreds of millions of neurons. Jan's BMI sampled only a few hundred of those neurons. Rather than a natural, almost unconscious movement, using the limb still requires some thought and practice. Such movement is much less difficult than with traditional prostheses but is still limited by the bandwidth of the

BMI. Despite its limitations, today's technology provides us with a glimpse of what might be achievable in the future.

There is also a significant technical issue with the "I" in BMI. To date, the interface has required a surgical implant in the brain. Some individuals may be undeterred by such an invasive procedure, but for many, elective brain surgery is reason enough to walk away. If not, it bears mentioning that the brain is rather inhospitable to foreign objects, limiting the utility of today's devices to several years—not the lifetime that we would want. However, this is a hurdle and not a barrier. Many researchers are working to increase the capability of minimally-invasive BMI technology, and developments look promising. Decades of research and investment in sensing technologies are coming together to bring the possibility of a noninvasive, ball-cap type BMI within the realm of the possible—eliminating today's barriers to widespread use of BMI.

Cost also remains a practical issue. Today, in part because of the necessity of surgery, BMI is expensive—too expensive for widespread application. But there is already evidence that the costs will come down exponentially over time, as they have with many other technical advances.

Money and technology aside, popular perceptions of BMI—and with them the policies and laws that will govern development—are essential to the future of this technology and should be at the top of the "what to think about next" list. We have already witnessed these same conversations related to genetic engineering and autonomous systems. The debate often reveals opposite positions: Either the future will be a technology-enabled utopia or a tragic, science fiction-like dystopia. Because the nuances of the issue are so complicated, we often exaggerate both the negative and positive. At the same time, real answers to public questions about the technology are as difficult for professional ethicists to answer as they are for expert technologists. Take, for example, our work with prosthetics patients. It was a breakthrough, tear-inducing moment when the signal processors for the BMI decoded signals from one of our participants and correctly moved the arm. But put another way, we succeeded in reading a person's mind (albeit crudely at that point). What does that mean for privacy in the future? How could this data affect us in unintended ways? And finally, how should we control access to the data? Likewise, breakthroughs in sensory feedback through BMI have incredible therapeutic potential and could also enable a level of control over machines that would truly be a game changer. But while one person

might think of it as enabling human senses, another might see it as putting ideas into someone's head. How can we use this technology to help individuals, while preventing its ability to do them harm?<sup>8</sup> And perhaps most esoteric but still important to our society: does this technology stand to change what it means to be human?

There is no doubt that BMI technology today is having a positive impact by restoring sight and sound, enabling the paralyzed to move, reducing the effects of Parkinson's disease, and offering the promise to treat other neurological conditions. At the same time, BMI could help the nation to address pressing national security concerns. As developers, it is our responsibility to balance these benefits through a sustained dialog between all parties. Many examples show that perceptions about AI are shaped by experiences and exposure. With that in mind, we must be careful to thoughtfully develop the first prototypes and interactions with this technology such that social norms evolve along with the technology and technology is informed by social norms.

As part of this discussion, it is useful to remember what we have learned from Jan, Tim, Johnny, and all those who have participated in similar BMI research projects. It is not about the technology alone but the positive impact BMI can have for all of us, both in improving health and in keeping the nation secure. Jan best reflected this sentiment in a note to the team upon learning that her BMI implants were to be removed:

And how I am feeling now is this: I've had the time of my life! This is been a fantastic, thrilling, wild ride, and I am so glad I've done this. Being part of this study has enriched my life, given me new friends and coworkers, helped me once again to be a contributing member of society, and taken my breath away. Ever since it began, in my morning prayers, I have thanked God every day for being able to be part of this study. And the rest of my life, I will thank God every day for having been part of this. I have no regrets. . . . I'm sure I will wake up one day in a couple weeks and just sob because I can't go into the lab to work with [the prosthetic limb] anymore. But what I don't think will happen is I will get depressed in the long run. I did this, and no one can ever take that away from me. Long after my name is forgotten, and the names of all the scientists who worked on this project are forgotten, our work will stand and will benefit future generations of paralyzed people and amputees.

BMI is a technology with enormous potential that deserves more attention, resourcing, and development. While it is not generally acces-

sible today, technologists, ethicists, and the public should consider its implications now. **SSQ**

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**Notes**

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