# NEURALINK

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## ABSTRACT

Brain-machine interfaces hold promise for the restoration of sensory and motor function and the treatment of neurological disorders, but clinical brain-machine interfaces have not yet been widely adopted, in part, because modest channel counts have limited their potential. In this white paper, we describe Neuralink's first steps toward a scalable high-bandwidth brain-machine interface system. We have built arrays of small and flexible electrode "threads," with as many as 3072 electrodes per array distributed across 96 threads. We have also built a neurosurgical robot capable of inserting six threads (192 electrodes) per minute. Each thread can be individually inserted into the brain with micron precision for avoidance of surface vasculature and targeting specific brain regions. The electrode array is packaged into a small implantable device that contains custom chips for low-power on-board amplification and digitization: The package for 3072 channels occupies less than 23×18.5×2 mm3. A single USB-C cable provides full-bandwidth data streaming from the device, recording from all channels simultaneously. This system has achieved a spiking yield of up to 70% in chronically implanted electrodes. Neuralink's approach to brain-machine interface has unprecedented packaging density and scalability in a clinically relevant package.

## KEYWORDS

Brain-machine interface, sensory function, motor function, neurology

## INTRODUCTION

Brain-machine interfaces have the potential to help people with a wide range of clinical disorders. For example, researchers have demonstrated human neuroprosthetic control of computer cursors robotic limbs and speech synthesizers by using no more than 256 electrodes. Although these successes suggest that high-fidelity information transfer between brains and machines is possible, development of brain-machine interface has been critically limited by the inability to record from large numbers of neurons. Non-invasive approaches can record the average of millions of neurons through the skull, but this signal is distorted and nonspecific. Invasive electrodes placed on the surface of the cortex can record useful signals, but they are limited in that they average the activity of thousands of neurons and cannot record signals deep in the brain. Most brain-machine interfaces have used invasive techniques, because the most precise readout of neural representations requires recording single action potentials from neurons in distributed, functionally linked ensembles. Microelectrodes are the gold-standard technology for recording action potentials, but there is no clinically translatable microelectrode technology for large-scale recordings. This would require a system with material properties that provide high biocompatibility, safety, and longevity. Moreover, this device would also need a practical surgical approach and high-density, low-power electronics to ultimately facilitate fully implanted wireless operation. Most devices for long-term neural recording are arrays of electrodes made from rigid metals or semiconductors. Although rigid metal arrays facilitate penetrating the brain, the size, young modulus, and bending stiffness mismatches between stiff probes and brain tissue can drive immune responses that limit the function and longevity of these devices. Furthermore, the fixed geometry of these arrays constrains the populations of neurons that can be accessed, especially due to the presence of vasculature. An alternative approach is to use thin, flexible multielectrode polymer probes . The smaller size and increased flexibility of these probes should offer greater biocompatibility. However, a drawback of this approach is that thin polymer probes are not stiff enough to directly insert into the brain; their insertion must be facilitated by stiffeners, injection, or other approaches, all of which are quite slow. To satisfy the functional requirements for a high-bandwidth brain-machine interface, while taking advantage of the properties of thin-film devices, we developed a robotic approach, where large numbers of fine and flexible polymer probes are efficiently and independently inserted across multiple brain regions. Here, we report Neuralink’s progress toward a flexible, scalable brain-machine interface that increases channel count by an order of magnitude over prior work. Our system has three main components: ultra-fine polymer probes, a neurosurgical robot, and custom high-density electronics. We demonstrate the rapid implantation of 96 polymer threads, each thread with 32 electrodes, yielding a total of 3072 electrodes. We developed miniaturized custom electronics that allow us to stream full broadband electrophysiology data simultaneously from all these electrodes. We packaged this system for long-term implantation and developed custom online spike-detection software that can detect action potentials with low latency. Together, this system serves as a state-of-the-art research platform and the first prototype toward a fully implantable human brain-machine interface.

## ELECTROPHYSIOLOGY

We have implanted both Systems A and B in male Long-Evans rats, as described in the section Robot. All animal procedures were performed in accordance with the National Research Council’s Guide for the Care and Use of Laboratory Animals and were approved by the Neuralink Institutional Animal Care and Use

Committee. Electrophysiological recordings were taken as the animals freely explored an arena equipped with a commutated cable that permitted unrestricted movement. System A can record 1344 of 1536 channels simultaneously; the exact channel configuration can be arbitrarily specified at the time of recording; System B can record from all 3072 channels simultaneously. Digitized broadband signals were processed in real time to identify action potentials (spikes) using an online detection algorithm. Spike detection requirements for real-time brain-machine interface are different from most conventional neurophysiology requirements. While most electrophysiologists spike-sort data offline and spend significant effort to reject false-positive spike events, brain-machine interface events must be detected in real time and spike detection parameters must maximize decoding efficacy. Using our custom online spike-detection software, we found that a permissive filter that allows an estimated false-positive rate of approximately 0.2 Hz performs better than setting stringent thresholds that may reject real spikes.

## ROBOT

Thin-film polymers have previously been used for electrode probes [21], but their low bending stiffness complicates insertions. Neuralink has developed a robotic insertion approach for inserting flexible probes [28], allowing rapid and reliable insertion of large numbers of polymer probes targeted to avoid vasculature and record from dispersed brain regions. The robot's insertion head is mounted on a globally accurate, 400×400×150 mm travel, 10-µm three-axis stage and holds a small, quick-swappable "needle-pincher". The robot registers insertion sites to a common coordinate frame with landmarks on the skull, which, when combined with depth tracking, enables precise targeting of anatomically defined brain structures. An integrated custom software suite allows preselection of all insertion sites, enabling planning of insertion paths optimized to minimize tangling and strain on the threads. The planning feature highlights the ability to avoid vasculature during insertions, one of the key advantages of inserting electrodes individually. This is particularly important, since damage to the blood-brain barrier is thought to play a key role in the brain's inflammatory response to foreign objects.

## ELECTRONICS

Chronic recording from thousands of electrode sites presents significant electronics and packaging challenges. The density of recording channels necessitates placing the signal amplification and digitization stack within the array assembly; otherwise, the cable and connector requirements would be prohibitive. This recording stack must amplify small neural signals (<10 µVRMS) while rejecting out-of-band noise, sample and digitize the amplified signals, and stream out the results for real-time processing—all using minimal power and size. The electronics are built around our custom Neuralink application-specific integrated circuit (ASIC), which consists of 256 individually programmable amplifiers ("analog pixels"), on-chip analog-to-digital converters (ADCs), and peripheral control circuitry for serializing the digitized outputs.

The analog pixel is highly configurable: The gains and filter properties can be calibrated to account for variability in signal quality due to process variations and the electrophysiological environment. The on-chip ADC samples at 19.3 kHz with 10-bit resolution. Each analog pixel consumes 5.2 μW, and the whole ASIC consumes approximately 6 mW, including the clock drivers. The Neuralink ASIC forms the core of a modular recording platform that allows for easy replacement of constitutive parts for research and development purposes. In the systems discussed here, a number of ASICs are integrated into a standard PCB using flip-chip integration. Each system consists of a field-programmable gate array; real-time temperature, accelerometer, and magnetometer sensors; and a single USB-C connector for full-bandwidth data transfer. The systems are packaged in titanium cases that are coated with parylene-c, which serves as a moisture barrier to prevent fluid ingress and prolong functional lifetime.

## CONCLUSION

We have described a brain-machine interface with a high-channel count and single-spike resolution. It is based on flexible polymer probes, a robotic insertion system, and custom low-power electronics. This system serves two main purposes: It is a research platform for use in rodents and serves as a prototype for future human clinical implants. The ability to quickly iterate designs and testing in rodents allows for the rapid refinement of devices, manufacturing processes, and software. Because it is a research platform, the system uses a wired connection to maximize the bandwidth for raw data streaming. This is important for performance assessments and crucial for the development of signal processing and decoding algorithms. In contrast, the clinical devices that derive from this platform will be fully implantable, which requires hermetic packaging, and have on-board signal compression, reduced power consumption, wireless power transmission, and data telemetry through the skin without percutaneous leads. Modulating neural activity will be an important part of next-generation clinical brain-machine interfaces , for example, to provide a sense of touch or proprioception to neuroprosthetic movement control. Therefore, we designed the Neuralink ASIC to be capable of electrical stimulation on every channel, although we have not demonstrated these capabilities here. This brain-machine interface system has several advantages over previous approaches. The size and composition of the thin-film probes are a better match for the material properties of brain tissue than commonly used silicon probes and may therefore exhibit enhanced biocompatibility . In addition, the ability to choose where our probes are inserted, including into the subcortical structures, allows us to create custom array geometries for targeting specific brain regions while avoiding vasculature. This feature is significant for creating a high-performance brain-machine interface, as the distribution of electrodes can be customized depending on the task requirements. Lastly, the miniaturization and design of the Neuralink ASIC affords great flexibility in system design and supports very high channel counts within practical size and power constraints. In principle, our approach to brain-machine interfaces is highly extensible and scalable. Here, we report simultaneous broadband recording from over 3000 inserted electrodes in a freely moving rat. In a larger brain, multiple devices with this architecture could be readily implanted, and we could therefore interface with many more neurons without extensive re-engineering. Further development of surgical robotics could allow us to accomplish this without dramatically increasing surgery time. Although significant technological challenges must be addressed before a high-bandwidth device is suitable for clinical application, with such a device, it is plausible to imagine that a patient with spinal cord injury could dexterously control a digital mouse and keyboard. When combined with rapidly improving spinal stimulation techniques, in the future, this approach could conceivably restore motor function. High-bandwidth neural interfaces should enable a variety of novel therapeutic possibilities.

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