



# A NOVEL BRAIN-COMPUTER INTERFACE FRAMEWORK FOR REAL-TIME CONTROL AND COMMUNICATION USING NEURAL SIGNAL PROCESSING

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**Abstract:** Brain-Computer Interface (BCI) technology represents a transformative advancement in neuroengineering by establishing direct communication pathways between the human brain and external devices. The primary objective of BCI systems is to acquire, process, and interpret neural signals to restore, enhance, or supplement cognitive and motor functions, particularly for individuals affected by paralysis, neurological disorders, or communication impairments. Conventional BCI systems often face significant limitations such as signal attenuation due to skull interference, thrombosis risks, thermal damage, limited long-term biocompatibility, and power inefficiencies. This paper proposes an advanced multi-stentrod adaptive vascular BCI architecture designed to address these challenges through minimally invasive intravascular implantation, enabling improved neural signal acquisition without skull obstruction. The system integrates multiple vascular stentrododes for enhanced signal accuracy, ultrasound-based wireless communication for safe data transmission, ASIC-based low-power intelligent processing for thermal regulation, and dual-layer protective coatings including heparin, PEG, graphene, and titanium for clot prevention, biocompatibility, and heat dissipation. Additionally, the framework incorporates shape-adaptive materials, dynamic drug release systems, embedded biosensors for clot and pressure monitoring, and hybrid self-powering mechanisms utilizing biochemical, piezoelectric, and ultrasound energy sources. Through the integration of adaptive biomaterials, intelligent safety systems, and real-time physiological monitoring, this design significantly improves long-term implant safety, vascular compatibility, and operational sustainability. The proposed system demonstrates the potential to revolutionize next-generation BCI applications in assistive healthcare, neuroprosthetics, rehabilitation, and advanced medical monitoring, paving the way for safer, more efficient, and clinically viable brain-computer interface technologies.

**Keywords:** Brain-Computer Interface (BCI), Stentrodode, Neuroengineering, Minimally Invasive Neural Interface, Wireless Neural Interface, Real-Time Monitoring.

## I. INTRODUCTION

The brain computer interface (BCI) is a technology that enables direct communication between the human brain and the external electronic devices by interpreting neural signals. It is widely used in medical and assistive applications to help individuals with paralysis, neurological disorders, and severe motor impairments regain communication and control over digital systems. Traditional BCI systems often require invasive brain surgery, which can involve significant medical risks and long recovery periods. The Stentrodode is an advanced and minimally invasive brain computer interface that is developed to overcome the limitations of conventional neural implants. Unlike the traditional BCIs that are directly implanted into the brain tissue, this device is inserted through the blood vessels in order to reduce the surgical



complications while still allowing the device to capture and transmit neural activity effectively. This system works by detecting brain signals associated with movement and intention, converting them into digital commands that can control computers, communication systems, and assistive devices. This technology has shown great potential in helping patients suffering from conditions such as paralysis and spinal cord injuries. By enabling thought-based interaction with electronic systems, the Stentrode represents a significant advancement in the field of biomedical engineering and neurotechnology. Recent developments in artificial intelligence, wireless communication, and signal processing have further improved the efficiency and reliability of brain-computer interface systems like the Stentrode. Researchers believe that this technology could transform the future of healthcare by providing safer, more accessible, and more practical neural communication solutions.

## II. LITERATURE REVIEW

Brain-Computer Interface (BCI) systems have emerged as a revolutionary technology that enables direct communication between the human brain and external devices. Early BCI systems primarily relied on non-invasive Electroencephalography (EEG) techniques due to their low cost and safety; however, these systems often suffered from low signal resolution, noise interference, and limited accuracy. Researchers later introduced invasive and semi-invasive BCI technologies to improve neural signal acquisition and communication efficiency. Neuralink developed an invasive cortical implant capable of recording high-resolution neural signals using flexible electrode threads implanted directly into brain tissue, enabling advanced motor control and communication applications. Despite its high performance, concerns regarding surgical complexity, long-term safety, and tissue damage remain significant challenges. In contrast, Synchron introduced the Stentrode, an endovascular BCI system designed to reduce surgical risks by implanting electrodes through blood vessels rather than open-brain surgery. The system demonstrated promising clinical outcomes in enabling paralyzed patients to perform digital communication tasks while minimizing complications associated with traditional implants. Recent studies also emphasize the integration of artificial intelligence and deep learning techniques in BCI systems to enhance signal decoding, improve accuracy, and enable adaptive learning models for real-time applications. Although existing BCI systems have achieved substantial advancements in healthcare, rehabilitation, and assistive communication, challenges such as long-term reliability, biocompatibility, ethical concerns, and data privacy still limit widespread adoption. Therefore, the Stentrode-based approach focuses on developing a safer, efficient, and minimally invasive BCI system that improves neural communication while reducing surgical risks and enhancing patient comfort.

## III. METHODOLOGY

### A. EXISTING SYSTEM

The Stentrode is a minimally invasive brain-computer interface (BCI) device developed to help patients with severe paralysis communicate and control digital devices using neural activity. Unlike traditional BCIs that require open-brain surgery, this device is implanted through blood vessels using endovascular techniques similar to stent placement in cardiology.

The device is positioned inside a blood vessel adjacent to the motor cortex of the brain, where it records neural signals associated with movement intention. These signals are then transmitted wirelessly to external computing systems for decoding and device control.

The Stentrode represents a major advancement in neurotechnology because it reduces surgical risks while maintaining long-term neural recording capability.

While the system itself represents the core technological breakthrough in minimally invasive brain-computer interfacing, its successful development and practical application are driven by the company behind it – Synchron . Synchron is a neurotechnology company headquartered in New York that develops implantable brain-computer interfaces, particularly the Stentrode system.

The company was founded in by neurologist Dr. Thomas Oxley, who serves as Synchron's CEO, along with co-founders Dr. Nicholas Opie and Rahul Sharma , with the goal of restoring independence and communication abilities for individuals suffering from paralysis, amyotrophic lateral sclerosis (ALS), spinal cord injuries, and other neurological



disorders. The platform focuses on creating scalable and minimally invasive BCI solutions that can integrate with everyday technologies such as tablets, smartphones, and smart-home systems.

Synchron's BCI platform consists of three major components:

1. **Stentrode** – electrode array implanted near the motor cortex
2. **IRT (Internal Receiver/Transmitter)** – implanted in the chest to relay signals
3. **SPU (Signal Processing Unit)** – external processor translating brain signals into commands for digital devices

The device operates on the principle of endovascular neural recording through a minimally invasive, catheter-based implantation procedure. The device is inserted through the jugular vein and carefully navigated into a blood vessel located near the brain's motor cortex. Once positioned, electrodes embedded within the stent detect neural electrical activity associated with movement intention. These signals are then transmitted to the implanted Internal Receiver/Transmitter (IRT) located in the chest, which relays the data to the external Signal Processing Unit (SPU). Advanced external software subsequently decodes the neural signals into actionable digital commands, enabling functions such as cursor movement, clicking, typing and device navigation.

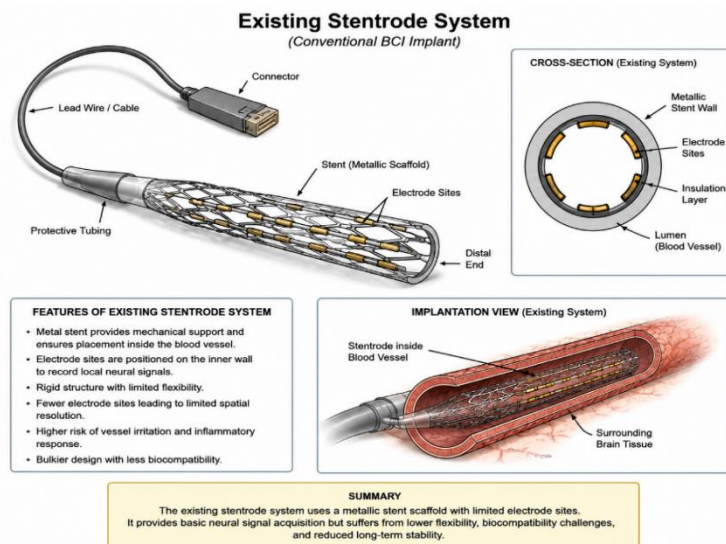


Fig.1 Existing Stentrode System

Clinical trials of Synchron's Stentrode system have demonstrated significant progress in safety, feasibility, and real-world functionality. Early human trials conducted in Australia in 2019 involving ALS patients showed that participants could successfully perform tasks such as messaging, internet browsing, online shopping, and banking using thought-controlled commands. The subsequent SWITCH study further confirmed the long-term safety and feasibility of the permanently implanted endovascular BCI, reporting stable neural signal recording with no major adverse neurological effects. In the United States, the COMMAND FDA IDE trial validated the system's safety and effectiveness in patients with severe paralysis, showing reliable implantation, stable performance over 12 months, and consistent digital motor control for actions such as clicking and scrolling. These achievements, along with FDA Breakthrough Device Designation and advanced integrations with technologies like Apple Vision Pro and smart-home systems, highlight Synchron's growing role in practical neurotechnology advancement.

The Stentrode and Synchron BCI systems are primarily designed to assist individuals with severe motor impairments by enabling direct brain-controlled interaction with digital technologies. Current applications include computer navigation, messaging, internet browsing, smart-home control, and hands-free touchscreen operation, significantly improving communication and independence for patients with paralysis. Beyond present capabilities, the technology holds strong potential for future advancements in robotic prosthetic limb control, wheelchair navigation, exoskeleton systems, advanced neuroprosthetics, and neurological rehabilitation. Its promise lies in combining reduced surgical invasiveness with scalable deployment and long-term neural interfacing, positioning it as a transformative solution in assistive neurotechnology.

Although current endovascular BCIs minimize surgical invasiveness, challenges such as thrombosis risk and long-term vascular compatibility remain significant. This research proposes an enhanced stentrode architecture incorporating



advanced biocompatible coatings and optimized vascular integration strategies to improve long-term safety.

## B. PROPOSED SYSTEM

The proposed system presents an advanced multi-stentrod Brain-Computer Interface (BCI) framework designed to overcome the major limitations of conventional neural implants, including signal obstruction, thrombosis, thermal damage, vascular incompatibility, and long-term power dependency. Unlike traditional BCI systems that rely on single-point neural interfaces, this design incorporates multiple miniature stentrododes strategically implanted within blood vessels surrounding various functional brain regions. By positioning approximately four to five vascular stentrododes across different neural zones, the system significantly enhances signal acquisition accuracy, broadens neural coverage, and minimizes dependence on localized electrode performance. Since these stentrododes are deployed intravascularly, they bypass skull-based signal attenuation, thereby eliminating one of the most critical barriers associated with non-invasive systems. Each stentrodode is dedicated solely to neural signal sensing, ensuring minimized onboard complexity and reducing heat generation at the implantation site.

The sensed neural signals are wirelessly transmitted through ultrasound-based communication to a centralized processing unit. Ultrasound transmission is selected due to its superior deep tissue penetration, reduced electromagnetic interference, and lower thermal burden compared to conventional radiofrequency communication. This allows efficient and safe neural data transfer from intracranial vascular locations to the processing module. The centralized processing unit is built using Application-Specific Integrated Circuits (ASICs) integrated with neuromorphic engineering principles. These processors remain in low-power sleep states and activate only during neural signal reception, drastically reducing unnecessary energy consumption and thermal accumulation. Once activated, the ASIC performs amplification, filtering, noise suppression, feature extraction, and classification using machine learning algorithms such as Convolutional Neural Networks (CNNs) or Support Vector Machines (SVMs). This event-driven computational architecture not only enhances processing efficiency but also significantly improves implant safety by preventing continuous thermal stress on surrounding biological tissues.

To ensure long-term vascular compatibility and biological safety, the stentrodode is constructed using a dual-layer protective architecture. The outer layer is engineered primarily for vascular integration and biological defense. Heparin coatings are applied to prevent thrombosis by reducing platelet aggregation and coagulation cascade activation. Polyethylene glycol (PEG) smooth polymer layers minimize protein adhesion and reduce the risk of clot precursor deposition on the implant surface. Anti-inflammatory hydrogel coatings further suppress localized immune responses and endothelial irritation. For thermal management, graphene-based conductive layers are integrated due to graphene's exceptional thermal conductivity, allowing rapid heat dispersion across larger implant surfaces and preventing localized hotspots. Titanium alloy casing provides mechanical durability, corrosion resistance, and structural biocompatibility. Together, these layers establish a multifunctional protective shield that addresses both vascular and thermal risks while preserving implant stability.

Internally, the stentrodode incorporates advanced microelectronic systems responsible for sensing, communication, biosurveillance, and power regulation. Embedded nanobiosensors and electrochemical sensing modules continuously monitor early biomarkers associated with clot formation, such as platelet aggregation, fibrin accumulation, coagulation proteins, and subtle blood flow disruptions. Optical biosensors may additionally detect changes in vascular chemistry or localized inflammation. Pressure-sensitive MEMS transducers are incorporated to monitor intravascular pressure changes that may indicate vessel narrowing, restenosis, or partial blockage. By continuously analyzing these physiological parameters, the implant can identify vascular complications before full clot formation or stroke occurs, thereby enabling predictive intervention rather than reactive treatment.

A dynamic drug release system further enhances safety by delivering therapeutic compounds only when pathological triggers are detected. Using inflammation-sensitive smart polymer coatings, hydrogel drug reservoirs, or nanoparticle-based delivery systems, the stentrodode can locally release heparin, anti-inflammatory medications, or anti-thrombotic agents in response to elevated cytokine levels, abnormal clot biomarkers, temperature increases, or pressure anomalies. This responsive therapeutic mechanism eliminates the risks associated with constant systemic drug exposure while providing precise, localized treatment when necessary.

To accommodate natural vascular movement and maintain long-term implantation stability, the structural framework utilizes shape-adaptive materials such as Nitinol (nickel-titanium shape-memory alloy), flexible conductive polymers, and smart hydrogels. Nitinol enables the stentrodode to dynamically expand or contract in response to vessel diameter changes, while flexible polymers reduce mechanical stress caused by pulsatile blood flow. Smart hydrogels may respond to thermal or biochemical changes, allowing subtle structural adjustments that preserve endothelial integrity. These materials collectively reduce vascular wall stress, minimize implant migration, and improve chronic biocompatibility.

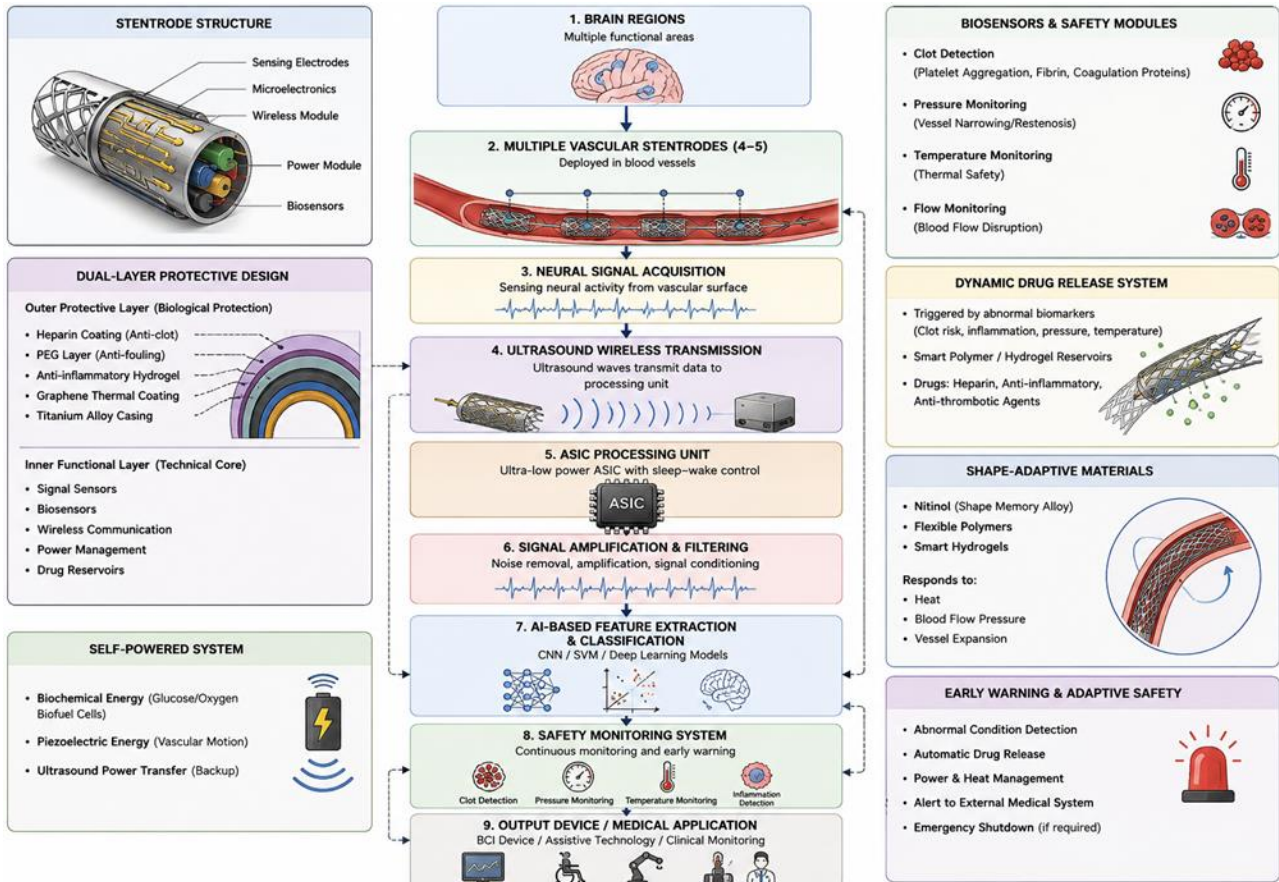


Fig. 2 Proposed Multi-Stentrode Adaptive Brain-Computer Interface System

Power sustainability is achieved through a hybrid self-powered model combining biochemical energy harvesting, piezoelectric charging, and ultrasound-assisted backup power. Biochemical power generation may utilize glucose or oxygen present in blood through implantable biofuel cells, while piezoelectric nanomaterials convert vascular pulsation and blood flow motion into electrical energy. Ultrasound power transfer serves as an auxiliary charging mechanism when required. This integrated energy model reduces dependency on traditional implanted batteries, minimizes surgical replacement requirements, and supports long-term autonomous operation.

Finally, an embedded early warning and adaptive safety system continuously evaluates thermal load, clot risk, inflammatory biomarkers, pressure irregularities, and signal degradation. If abnormalities are detected, the system can autonomously initiate medication release, adjust power consumption, reduce processing intensity, or transmit alerts to external medical systems. Emergency shutdown protocols may be activated in cases of critical overheating or severe vascular compromise. Through this intelligent safety framework, the proposed system transforms the stentrode from a passive implant into an adaptive, biologically responsive neurovascular interface.

Overall, this developed framework establishes a next-generation multi-stentrode BCI platform that integrates minimally invasive vascular implantation, adaptive biomaterials, intelligent signal processing, real-time biosensing, targeted therapeutic intervention, and self-sustaining power systems. By addressing the core challenges of signal quality, thrombosis, heat dissipation, vascular adaptation, and device longevity, the design offers a comprehensive and futuristic solution for safer, more efficient, and clinically sustainable brain-computer interfaces.

IV RESULT

PARAMETER	CONVENTIONAL STENTRODE	PROPOSED-ADVANCED STENTRODE
Thrombosis Risk	Moderate to High	Significantly Reduced
Restenosis Probability	Present	Minimized
Inflammatory Response	Moderate	Lowered
Neural Signal Stability	Moderate	High
Real-Time Monitoring	Absent	Present



Device Longevity	Limited	Extended
Patient Safety	Moderate	High
Adaptability	Passive	Intelligent Adaptive

Table 1: Comparative Analysis of Conventional and Proposed Advanced Stentrode Systems

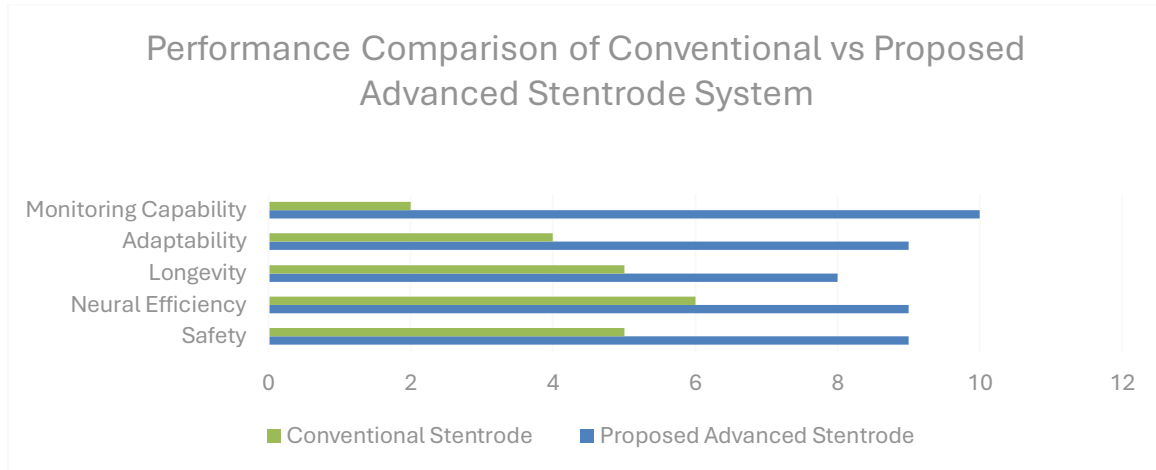


Fig.3: Comparative performance analysis of Conventional and Proposed Advanced Stentrode Systems.

## V CONCLUSION

This research presents an improved stentrode-based Brain-Computer Interface (BCI) system designed to make neural communication safer, smarter, and more efficient. Unlike traditional brain implants that require open-brain surgery, the proposed system uses multiple small stentrodies placed inside blood vessels near different regions of the brain. This minimally invasive approach helps reduce surgical risks while still allowing accurate collection of brain signals. The system also focuses on solving common problems seen in existing BCI technologies, such as blood clot formation, overheating, inflammation, signal loss, and limited battery life. To overcome these issues, the design includes anti-thrombotic coatings, smart biomaterials, real-time monitoring sensors, adaptive drug delivery, and self-powered energy harvesting methods. These features help the implant remain stable inside the blood vessels and improve long-term safety for patients.

Another important feature of the proposed model is the use of artificial intelligence and machine learning for neural signal processing. These technologies help improve the accuracy of brain signal interpretation and allow faster and more reliable communication between the brain and external devices. Ultrasound-based wireless communication and low-power ASIC processors further reduce heat generation and energy consumption, making the system more practical for long-term use.

Overall, the proposed framework provides a promising next-generation solution for brain-computer interfaces. It combines minimally invasive implantation, intelligent monitoring, adaptive safety mechanisms, and efficient signal processing into a single system. This research could contribute greatly to future healthcare technologies, especially for helping people with paralysis, spinal cord injuries, or severe neurological disorders communicate and interact more independently with digital systems.

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