Control Systems and Adaptive Neurostimulation in Deep Brain Stimulation (DBS) for Treatment-Resistant Obsessive-Compulsive Disorder (TR-OCD): Architecture, Brain-Sensing, and Closed-Loop Strategies

Hedya Nadhrati Surura[1], Rina Hastuti Lubis[1], Nashrul Fazli Mohd Nasir[2], Joandre Fauza[3]
[1]Departement of Psychiatry, Universitas Syiah Kuala, Aceh, Indonesia
[2]Departement of Electronic Engineering, Universiti Malaysia Perlis, Perlis, Malaysia
[3]Departement of Neurosurgery, Universitas Malikussaleh, Aceh, Indonesia
Corresponden Author: rinahastutilubis@usk.ac.id

ABSTRACT

Deep Brain Stimulation (DBS) is an implantable neuromodulation technology used to treat treatment-resistant obsessive-compulsive disorder (TR-OCD). This review examines DBS system architecture, open-loop and closed-loop control strategies, neural biomarkers, and recent advances in adaptive neurostimulation. Conventional DBS operates using predefined stimulation parameters without real-time feedback, whereas emerging closed-loop DBS utilizes neural biomarkers, particularly local field potentials (LFPs), to automatically adjust stimulation based on brain activity. This adaptive approach has the potential to improve therapeutic effectiveness, increase energy efficiency, and enable personalized treatment. The integration of neural biomarkers, adaptive control algorithms, and connectomic approaches is expected to support the development of next-generation intelligent DBS systems and advance precision psychiatry for TR-OCD.

Keywords: Deep Brain Stimulation; Closed-Loop Control; Adaptive Neurostimulation; Neural Biomarkers; Treatment-Resistant Obsessive-Compulsive Disorder.

INTRODUCTION

Obsessive-compulsive disorder (OCD) is a chronic and disabling neuropsychiatric disorder characterized by persistent intrusive thoughts (obsessions) and repetitive behaviors (compulsions) that substantially impair quality of life and psychosocial functioning. Although pharmacological therapy using selective serotonin reuptake inhibitors (SSRIs) combined with cognitive behavioral therapy remains the first-line treatment, approximately 10–20% of patients develop treatment-resistant obsessive-compulsive disorder (TR-OCD), in which symptoms persist despite adequate conventional interventions (Meyer et al., 2024; Gadot et al., 2022; Acevedo et al., 2024).

Among currently available neuromodulation approaches, Deep Brain Stimulation (DBS) has emerged as one of the most promising therapies for TR-OCD.

DBS delivers programmable electrical stimulation through intracranial electrodes implanted within the cortico-striato-thalamo-cortical (CSTC) network, including the anterior limb of the internal capsule (ALIC), ventral capsule/ventral striatum (VC/VS), nucleus accumbens (NAcc), bed nucleus of the stria terminalis (BNST), and subthalamic nucleus (STN). Clinical studies have consistently demonstrated significant reductions in obsessive-compulsive symptoms following DBS implantation; however, therapeutic outcomes remain highly dependent on stimulation target selection, neural connectivity, and optimization of stimulation parameters (Gadot et al., 2022; Meyer et al., 2024; Horn et al., 2026).

From an engineering perspective, DBS represents a sophisticated implantable bioelectronic control system integrating implantable pulse generators (IPGs), intracranial electrodes, signal transmission pathways, and biological neural networks into a unified neuromodulation platform. Conventional DBS systems predominantly operate using an open-loop architecture, where stimulation is delivered continuously according to predefined parameters without incorporating real-time neurophysiological feedback. Although this strategy has demonstrated substantial clinical efficacy, it is inherently limited because pathological neural activity in OCD fluctuates dynamically over time, while stimulation parameters remain fixed throughout treatment sessions (Sellers et al., 2024; Fanty et al., 2023; Groppa et al., 2024).

Recent advances in neuroengineering have accelerated the development of adaptive or closed-loop DBS systems capable of sensing ongoing neural activity and automatically modifying stimulation parameters according to patient-specific neurophysiological states. The emergence of implantable brain-sensing technologies has enabled continuous recording of neural biomarkers, particularly local field potentials (LFPs), neural oscillations, and functional connectivity patterns that closely correlate with symptom severity. These biomarkers provide objective feedback signals that support adaptive control algorithms capable of optimizing stimulation intensity, timing, and duration while simultaneously improving therapeutic efficacy, minimizing adverse effects, and reducing implantable pulse generator energy consumption (Arbab et al., 2025; Sellers et al., 2024; Provenza et al., 2022; Nho et al., 2024). Simultaneously, rapid progress in computational neuroscience, connectomics, artificial intelligence, and biomedical signal processing has transformed DBS from a purely anatomical stimulation technique into an intelligent neuromodulation platform.

Modern adaptive DBS systems increasingly incorporate machine learning algorithms, predictive control strategies, and connectomic analyses to identify individualized neural signatures and facilitate precision neuromodulation. These multidisciplinary developments have positioned DBS at the intersection of neuroscience, psychiatry, biomedical engineering, electrical engineering, and control systems engineering, creating new opportunities for personalized treatment strategies in psychiatric disorders (Acharyya et al., 2025; Tian et al., 2024; Li et al., 2025; Cole & Miocinovic, 2025). Despite remarkable technological advances, current literature remains largely fragmented. Most published studies primarily emphasize clinical outcomes, stimulation targets, or surgical procedures, whereas comprehensive discussions integrating DBS hardware architecture, control system design, neural biomarkers, brain-sensing technologies, adaptive control algorithms, and future intelligent neuromodulation frameworks remain limited. A holistic systems-engineering perspective is therefore still lacking, despite being essential for understanding the evolution of next-generation adaptive DBS technologies (Fanty et al., 2023; Groppa et al., 2024; Whitestone et al., 2023). Accordingly, this narrative review aims to synthesize current evidence regarding the architecture of Deep Brain Stimulation systems, conventional open-loop and adaptive closed-loop control strategies, brain-sensing technologies, neural biomarkers, and emerging intelligent control algorithms for treatment-resistant obsessive-compulsive disorder. Furthermore, this review discusses future directions involving adaptive neurostimulation, artificial intelligence, and connectomic-guided neuromodulation as key foundations for next-generation precision psychiatry.

LITERATURE REVIEW.

2.1. Deep Brain Stimulation as a Neuromodulation System

Deep Brain Stimulation (DBS) is an implantable neuromodulation technology that delivers controlled electrical stimulation to specific brain structures through stereotactically implanted electrodes. Initially developed for movement disorders such as Parkinson's disease and essential tremor, DBS has increasingly been applied to neuropsychiatric disorders, particularly treatment-resistant obsessive-compulsive disorder (TR-OCD). Unlike lesion-based neurosurgical procedures, DBS provides reversible and adjustable modulation of dysfunctional neural circuits, enabling individualized therapeutic intervention while minimizing irreversible tissue damage (Fariba & Gupta, 2023; Sarica et al., 2021).

From an engineering perspective, DBS can be regarded as a bioelectronic control system consisting of an Implantable Pulse Generator (IPG), intracranial electrodes, extension leads, and biological neural tissue. The IPG functions as the controller that generates programmable electrical pulses, while the implanted electrodes serve as actuators delivering stimulation to target neural circuits. The therapeutic objective is to restore abnormal neural activity within the cortico-striato-thalamo-cortical (CSTC) network, which is critically involved in the pathophysiology of obsessive-compulsive disorder (Whitestone et al., 2023; Chen et al., 2024).

Recent technological developments have substantially improved DBS hardware through rechargeable batteries, directional electrodes, wireless telemetry, and current steering capabilities. These innovations enable more selective stimulation, improve spatial targeting accuracy, reduce current spread to adjacent tissues, and prolong device longevity (Attilio et al., 2025; Degirmenci, 2024).

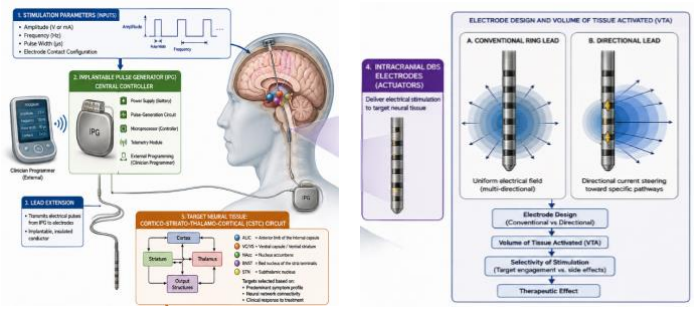

Figure 1. Architecture of the Deep Brain Stimulation (DBS) system for treatment-resistant obsessive-compulsive disorder (TR-OCD).

The DBS system consists of an implantable pulse generator (IPG), a lead extension, and intracranial electrodes implanted in specific neural targets, including the anterior limb of the internal capsule (ALIC), ventral capsule/ventral striatum (VC/VS), nucleus accumbens (NAcc), bed nucleus of the stria terminalis (BNST), and subthalamic nucleus (STN). From a control systems perspective, the IPG functions as the controller that generates programmable electrical stimulation, the intracranial electrodes serve as actuators, and the target neural circuitry acts as the plant being modulated to achieve therapeutic outcomes. Source: Created by the authors based on a synthesis of the reviewed literature.

2.2. Treatment-Resistant Obsessive-Compulsive Disorder

Obsessive-compulsive disorder is characterized by recurrent intrusive thoughts and repetitive compulsive behaviors that significantly impair psychosocial functioning. Although selective serotonin reuptake inhibitors (SSRIs) and cognitive behavioral therapy remain standard treatments, approximately 10–20% of patients experience persistent symptoms despite adequate treatment and are therefore classified as having treatment-resistant OCD (TR-OCD) (Meyer et al., 2024; Gadot et al., 2022).

The neurobiological basis of TR-OCD is strongly associated with dysfunction within the cortico-striato-thalamo-cortical (CSTC) circuitry. Hyperactivity involving the orbitofrontal cortex, anterior cingulate cortex, ventral striatum, and thalamic pathways contributes to impaired inhibitory control and persistent compulsive behaviors. Consequently, DBS therapy primarily targets structures such as the anterior limb of the internal capsule (ALIC), ventral capsule/ventral striatum (VC/VS), nucleus accumbens (NAcc), bed nucleus of the stria terminalis (BNST), and subthalamic nucleus (STN), all of which play essential roles in modulating dysfunctional neural networks (Horn et al., 2026; Provenza et al., 2024).

Clinical evidence consistently demonstrates significant reductions in Yale-Brown Obsessive Compulsive Scale (Y-BOCS) scores following DBS implantation, although treatment response varies considerably across patients because of differences in neural connectivity, disease heterogeneity, and stimulation programming (Acevedo et al., 2024; Abdelnaim et al., 2023).

2.3. Open-Loop Deep Brain Stimulation

Conventional DBS systems employ an open-loop control architecture in which stimulation parameters remain fixed after clinical programming. Electrical pulses are continuously delivered regardless of ongoing neural activity, and stimulation adjustments depend entirely on periodic clinical evaluations and manual device reprogramming performed by clinicians (Kachhadia et al., 2025). The simplicity and reliability of open-loop DBS have contributed to its widespread clinical implementation. Nevertheless, this approach cannot accommodate dynamic fluctuations in neural activity associated with psychiatric disorders such as OCD. Consequently, prolonged stimulation may lead to unnecessary energy consumption, increased battery depletion, overstimulation, and stimulation-related adverse effects (Widge, 2023; Widge, 2024).

Despite these limitations, open-loop DBS remains the current clinical standard because of its relatively simple architecture, established safety profile, and lower computational complexity compared with adaptive neuromodulation systems (Fanty et al., 2023).

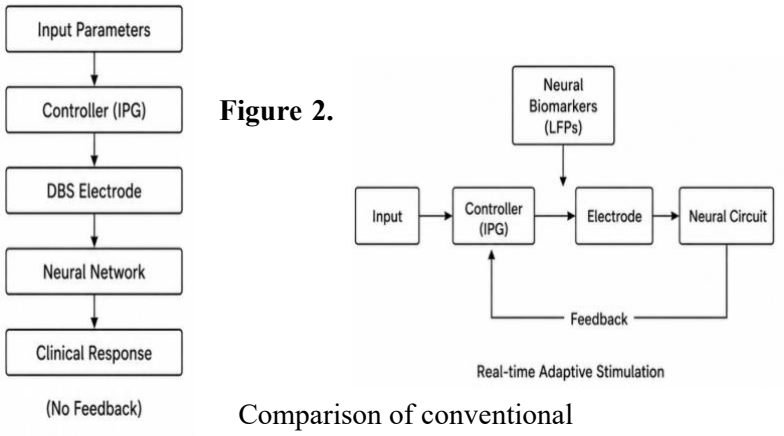

Figure 2. Comparison of conventional and adaptive Deep Brain Stimulation (DBS) control system architectures.

2.4. Closed-Loop Deep Brain Stimulation

Closed-loop DBS, also referred to as adaptive DBS (aDBS), represents the next generation of intelligent neuromodulation systems. Unlike conventional systems, adaptive DBS continuously records neural activity and dynamically modifies stimulation parameters based on physiological feedback. This architecture transforms DBS into a real-time feedback control system capable of responding to ongoing changes in neural network activity (Sellers et al., 2024). Adaptive DBS generally consists of four integrated modules: neural signal acquisition, signal processing, decision-making algorithms, and stimulation control. Neural biomarkers are continuously monitored, processed using computational algorithms, and subsequently utilized to determine appropriate stimulation adjustments.

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Consequently, adaptive DBS delivers stimulation only when pathological neural activity is detected, thereby improving therapeutic precision while reducing unnecessary stimulation (Groppa et al., 2024; Nho et al., 2024). Recent clinical investigations indicate that adaptive DBS may improve symptom control, extend battery life, reduce adverse effects, and provide greater personalization than conventional open-loop systems. However, widespread clinical implementation remains limited because reliable biomarkers and robust adaptive control algorithms are still under active investigation (Cole & Miocinovic, 2025).

Table 1. Comparison of Open-Loop and Closed-Loop Deep Brain Stimulation (DBS) Architectures

Parameter	Open-Loop DBS	Closed-Loop DBS
Control Strategy	Feed-forward control	Feedback-based control
Neural Feedback Availability	Not available	Available
Data Source	Predefined stimulation parameters	Neural biomarkers (e.g., LFPs, neural oscillations)
Stimulation Adjustment	Manual programming	Automated adaptive modulation
Response to Symptom Fluctuations	Limited	Real-time responsive
Energy Efficiency	Lower	Higher
IPG Battery Consumption	Higher	Lower
Device Complexity	Relatively low	Relatively high
Computational Requirements	Minimal	High
Degree of Personalization	Limited	High
Risk of Overstimulation	Higher	Lower
Potential Adverse Effects	Greater	Reduced
Current Clinical Status	Established standard therapy	Emerging and under active development
Future Clinical Potential	Moderate	Very high

2.5. Brain-Sensing Technologies and Neural Biomarkers

Brain-sensing technology constitutes the core enabling component of adaptive DBS. Modern implantable neurostimulators are capable of simultaneously delivering electrical stimulation and recording electrophysiological activity through implanted electrodes. This dual functionality enables continuous monitoring of neural biomarkers during therapy (Groppa et al., 2024). Among currently available biomarkers, local field potentials (LFPs) have emerged as the most extensively investigated because they reflect synchronized neuronal population activity surrounding implanted electrodes. Alterations in LFP oscillations within the CSTC circuitry correlate closely with obsessive-compulsive symptom severity, making them promising candidates for feedback-controlled neuromodulation (Arbab et al., 2025). Additional biomarkers include theta, alpha, beta, and gamma oscillatory activity, functional connectivity, and network synchronization measures obtained through computational neuroscience approaches. Machine learning techniques have further improved biomarker identification by integrating multiple electrophysiological features into individualized predictive models capable of detecting pathological brain states with greater accuracy (Bazarra Castro et al., 2024; Bervoets et al., 2022).

2.6. Adaptive Control Algorithms

Adaptive control algorithms represent the computational intelligence responsible for translating neural biomarkers into therapeutic stimulation commands. The simplest implementation employs threshold-based controllers that activate stimulation when biomarker amplitudes exceed predefined values. Although computationally efficient, threshold-based systems are limited by their inability to capture nonlinear brain dynamics (Busch et al., 2024).

Advanced adaptive controllers increasingly incorporate classical control engineering approaches such as Proportional-Integral-Derivative (PID) controllers and Model Predictive Control (MPC). These algorithms continuously estimate system errors and predict future neural states to optimize stimulation parameters before pathological symptoms fully develop (Tian et al., 2024). Recent progress in artificial intelligence has introduced machine learning, deep learning, and reinforcement learning into adaptive DBS. AI-driven controllers learn patient-specific neural activity patterns, enabling predictive and personalized neuromodulation strategies that continuously improve through ongoing interaction with recorded brain signals (Acharyya et al., 2025; Ravivarapu et al., 2025; Zhao et al., 2025).

METHOD.

This study employed a narrative review approach to synthesize recent evidence on Deep Brain Stimulation (DBS) for treatment-resistant obsessive-compulsive disorder (TR-OCD), focusing on system architecture, open-loop and closed-loop control strategies, brain-sensing technologies, neural biomarkers, adaptive neurostimulation, and intelligent control algorithms. Literature was retrieved from PubMed, Scopus, Web of Science, and IEEE Xplore using relevant keywords related to DBS, OCD, adaptive neurostimulation, and neural biomarkers. Peer-reviewed English-language articles published between 2021 and 2026 were included, while editorials, conference abstracts, and studies lacking sufficient technical or methodological information were excluded. Selected studies were analyzed using a thematic narrative synthesis, with findings organized into key themes including DBS architecture, control systems, brain-sensing technologies, neural biomarkers, adaptive algorithms, and future developments in intelligent neuromodulation.

This approach enabled the identification of current technological advances, research gaps, and future directions for precision psychiatry in the treatment of TR-OCD.

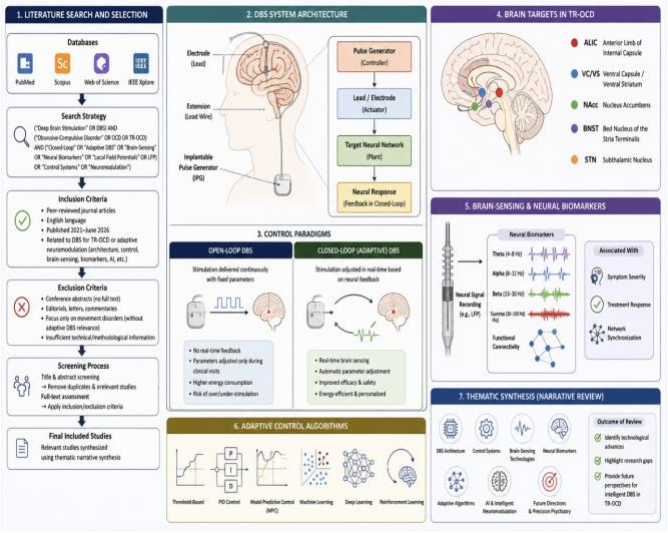

Figure 3. System Archytecture

RESULT.

tau analisis statistik, tetapi **hasil sintesis literatur**. Berikut bagian **Results** yang sesuai dengan standar jurnal **Scopus Q1**dan konsisten dengan metode yang telah dibuat.

4. Results

4.1. DBS System Architecture.

A total of recent peer-reviewed studies published between 2021 and 2026 were synthesized to evaluate the current development of Deep Brain Stimulation (DBS) for treatment-resistant obsessive-compulsive disorder (TR-OCD). The reviewed literature consistently demonstrates a transition from conventional continuous stimulation toward intelligent adaptive neuromodulation integrating brain-sensing technologies, neural biomarkers, and closed-loop control systems. The thematic synthesis identified six major areas of technological development, including (1) DBS system architecture, (2) open-loop stimulation systems, (3) closed-loop adaptive neurostimulation, (4) brain-sensing technologies and neural biomarkers,

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(5) adaptive control algorithms, and (6) future intelligent neuromodulation platforms.

Table 1. Summary of Major Findings from the Literature Review

Theme	Main Findings	Clinical Significance
DBS Architecture	IPG, electrodes, extension leads, CSTC modulation	Foundation of neuromodulation
Open-loop DBS	Continuous stimulation without feedback	Effective but limited adaptability
Closed-loop DBS	Real-time adaptive stimulation	Personalized therapy
Brain-sensing	LFPs and neural oscillations	Objective physiological feedback
Neural Biomarkers	LFP, beta, theta, gamma oscillations	Symptom detection
Adaptive Algorithms	Threshold, PID, MPC, AI, Deep Learning	Intelligent stimulation optimization
Future Direction	AI, Connectomics, Digital Twin, Precision Psychiatry	Next-generation neuromodulation

The reviewed studies consistently describe DBS as an implantable bioelectronic control system comprising an Implantable Pulse Generator (IPG), intracranial electrodes, extension leads, and target neural networks. The IPG functions as the central controller that generates programmable electrical stimulation delivered through implanted electrodes to modulate pathological activity within the cortico-striato-thalamo-cortical (CSTC) circuitry. Recent hardware developments, including rechargeable IPGs, directional electrodes, and wireless telemetry, have improved stimulation precision, reduced adverse effects, and extended device longevity (Sarica et al., 2021; Whitestone et al., 2023; Attilio et al., 2025).

4.2 Open-Loop Deep Brain Stimulation and Closed-Loop.

Most currently available clinical DBS systems continue to operate using an open-loop control strategy in which stimulation is delivered continuously according to predefined parameters without incorporating real-time neurophysiological feedback. Although this approach has demonstrated substantial clinical efficacy for TR-OCD, the literature consistently reports several limitations, including dependence on manual programming, inability to respond to fluctuating neural activity, increased battery consumption, and higher risk of overstimulation (Fanty et al., 2023; Widge, 2023; Kachhadia et al., 2025).

Table 2. Comparison of Open-Loop and Closed-Loop DBS Systems

Parameter	Open-Loop DBS	Closed-Loop DBS
Control Strategy	Feed-forward	Feedback control
Brain Sensing	Not Available	Available
Neural Biomarkers	No	Yes
Parameter Adjustment	Manual	Automatic
Response to Symptoms	Fixed	Real-time
Energy Efficiency	Moderate	High
Battery Consumption	High	Lower
Personalization	Low	High
Computational Requirement	Low	High
Clinical Status	Standard therapy	Emerging technology

Recent studies demonstrate increasing interest in adaptive or closed-loop DBS systems capable of continuously monitoring neural activity and automatically adjusting stimulation parameters according to patient-specific physiological conditions. Compared with conventional DBS, adaptive neurostimulation provides improved therapeutic precision, enhanced energy efficiency, and greater treatment personalization through real-time feedback mechanisms (Sellers et al., 2024; Groppa et al., 2024; Nho et al., 2024).

4.3. Brain-Sensing Technologies and Neural Biomarkers

The literature identifies brain-sensing capability as the primary technological innovation enabling adaptive DBS. Local field potentials (LFPs) remain the most extensively investigated neural biomarkers because they accurately reflect synchronized neuronal population activity within the CSTC network. Additional biomarkers include theta-, alpha-, beta-, and gamma-band oscillations, functional connectivity, and neural network synchronization. These biomarkers provide objective physiological information that enables adaptive stimulation according to ongoing disease activity (Arbab et al., 2025; Bazarra Castro et al., 2024).

Table 3. Characteristics of Selected Studies on Deep Brain Stimulation for TR-OCD

Author	Year	Study Design	Main Topic	Major Findings
Gadot et al.	2022	Systematic Review & Meta-analysis	Clinical efficacy of DBS	DBS significantly reduced OCD symptoms in patients with TR-OCD.
Fanty et al.	2023	Narrative Review	Current DBS technology	Open-loop DBS remains the clinical standard, but adaptive DBS shows promising future potential.
Sellers et al.	2024	Review	Closed-loop neurostimulation	Adaptive DBS improves therapeutic precision through neural feedback.
Provenza et al.	2024	Clinical Study	Neural periodicity	Neural periodicity predicts DBS therapeutic response.

4.4. Adaptive Control Algorithms

The reviewed literature indicates rapid development of adaptive control algorithms ranging from simple threshold-based controllers to advanced proportional-integral-derivative (PID), Model Predictive Control (MPC), machine learning, deep learning, and reinforcement learning approaches. These intelligent algorithms enable prediction of pathological neural activity and optimization of stimulation parameters before symptom exacerbation occurs, thereby improving both therapeutic efficacy and device efficiency (Tian et al., 2024; Acharyya et al., 2025; Zhao et al., 2025).

Table 4. Adaptive Control Algorithms

Algorithm	Principle	Advantages	Limitations
Threshold-Based	Fixed threshold	Simple implementation	Low adaptability
PID Controller	Error correction	Stable control	Requires parameter tuning
Model Predictive Control (MPC)	Predict future states	High precision	Computationally expensive
Machine Learning	Pattern recognition	Personalized control	Large datasets required
Deep Learning	Feature extraction	High prediction accuracy	Black-box interpretation
Reinforcement Learning	Self-learning optimization	Adaptive stimulation	High computational complexity

Recent investigations demonstrate that future DBS systems will increasingly integrate artificial intelligence, multimodal neural biomarkers, connectomic brain network analysis, and autonomous adaptive controllers into a unified intelligent neuromodulation platform. These technologies are expected to support precision psychiatry by providing personalized, predictive, and energy-efficient neurostimulation while reducing clinician programming burden (Li et al., 2025; Cole & Miocinovic, 2025).

CONCLUSION

Deep Brain Stimulation (DBS) has emerged as a promising neuromodulation therapy for treatment-resistant obsessive-compulsive disorder (TR-OCD) through the modulation of cortico-striato-thalamo-cortical (CSTC) circuits implicated in the pathophysiology of OCD. Recent technological advancements have driven a paradigm shift from conventional open-loop DBS systems toward adaptive closed-loop architectures that integrate neurophysiological biomarkers and brain-sensing technologies to dynamically adjust stimulation parameters in real time. This evolution has the potential to enhance therapeutic precision, improve energy efficiency, and facilitate individualized treatment strategies. Although further validation of neural biomarkers and optimization of control algorithms are still required, the convergence of neuroscience, psychiatry, control systems engineering, and biomedical engineering is expected to play a pivotal role in the development of next-generation DBS technologies. Ultimately, these advances may contribute to the realization of precision psychiatry and more effective neuromodulation therapies for patients with TR-OCD.

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