



Octopus Neural Control –Inspired Process Control Strategy for Biomedical Regulation

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ABSTRACT: Active regulation systems in biomedical settings demand an adaptive, reliable, and efficient control strategy under dynamic and uncertain circumstances. This paper presents a process control biomimetic strategy for biomedical regulation that takes inspiration from the octopuses decentralized, adaptive neural control system. With a distributed sensing operation, decision making is performed locally, actuating proportionally-a quite robust biological paradigm for real-time control with minimal centralized computation. In the proposed approach, the biomedical sensors measure the parameter and produce feedback signals similar to the function of sensory neurons in the octopus arm system. The proportional controller is used in imitating the adaptive response in the octopus neural control system, which reacts to error in proportion to its magnitude from the desired state. The biomedical process is described as a first-order system that can allow for transparent analysis and implementation. The controller's corrective action is based on the actuator, and there is a closed-loop feedback control system that maintains stability. Performance evaluation is carried out by analyzing time-domain parameters such as rise time, settling time, and steady-state error for variable controller gains. The results reveal enhanced accuracy of regulation and rapid response compared to open-loop operation. This octopus-inspired control strategy represents one of the low-cost, robust, and easy applications of biomedical uses for regulating physiological parameters and automated therapeutic systems.

Keywords: Biomimetic Control, Octopus Neural System, Closed-Loop Regulation, Biomedical Sensors, Process Control.

1. Introduction

Biomedical systems require effective and robust control solutions that can precisely control key physiological parameters under dynamic and uncertain environmental conditions. The existing control solutions used in other applications like robotics often fail and lack robustness due to physiological variability and uncertain physiological dynamics of biomedical [1]. To overcome such limitations and improve

robustness of biomedical under uncertain physiological dynamics and physiological variability, biomimetic control solutions can be used for adaptation purposes.

The octopus is an example of an aquatic creature with a very decentralized and agile nervous system. The body of the octopus has many neurons in its arms that are able to perceive, decide, and control without depending on its central nervous system. This very adaptive

mechanism is taken as an inspiration to develop real-time control systems in biomedicine where the computational complexity is minimal [2].

The issue dealt in this study is how to develop a sensor control system for the regulation of biological functions based on octopus adaptive neural control and classical process control. The goal is to regulate biological functions effectively while ensuring precise control, rapid response, and a small steady-state error.

The aim of the proposed study is to develop a proportional closed-loop control system, in which the parameter of interest is continuously measured by biomedical sensors, and the control actions are generated to correct the system, similar to the adaptability exhibited by octopus neural networks. The originality of the paper is in applying the principles gleaned from octopus control to biomedicine, which can be effective, according to the time-domain analysis performed. The study forms the basis for improving control systems in biomedicine by being intelligent and adaptive in the future [3].

2. Recent Works

Recent studies into biologically inspired control systems have investigated the specific decentralized neural behaviors of soft-bodied creatures like octopuses, and various applications of these principles into engineering and related biomedical research. From these electrophysiological studies, the following findings regarding octopus arms show how their neural systems are capable of localized processing and predictive analysis of motor function based on specific neural spiking patterns, effectively achieving adaptation to real-time feedback processes [1].

These specific data points regarding decentralized neural behaviors are clearly essential for understanding how sensor-controller interactions could function. Alongside these technologies, design frameworks supporting soft robotic systems have seen significant momentum.

In this context, Choi et al. proposed an octopus bio-inspired soft gripper sensing system comprising flexible sensor mapping and shape control through AI-powered feedback loops to support adaptive manipulation in high compliance [2].

The proposed sensing control system is explained to consist of signal processing from several embedding sensors in the system, along with proportional control to pneumatically driven actuators—that closely follows the sensor-actuator configuration in biomedical CL systems. Another new development is the Magoctopus line of magnetic soft robots, whose morphing activities can be controlled programmatically through magnetic field actuation and show the abilities to track paths and transport specific payload. These robotic systems include control routines whose shape and movement dynamics can be changed based on feedback factors, therefore exemplifying the possibility to apply biological principles in the design of actuation and feedback systems in robotics [3].

These robotic systems can be used in biomedical regulation because they have reusable control paths. Together, these works illustrate how the principles of distributed sensory feedback, proportional actuation, and adaptive algorithms inspired by octopus neural control have been applied to a range of engineering systems. However, direct application to biomedical closed-loop regulation remains scant, which is the motivation for the focus of the present work on integrating these biomimetic principles with classical process control strategies in physiological systems.

3. Proposed Work and Theoretical Background

This proposed work is an extension of traditional process control, drawing inspiration from octopus adaptive neural control. In contrast to traditional centralized control, this approach simulates the decentralized sensing and proportional control

present in octopus arms. While biomedical sensors sense biomedical parameters in a manner similar to peripheral neurons, a proportional controller computes a corrective output proportional to a sensed difference. To keep things analytical and simple, a first-order dynamic process is assumed. This provides a foundation for real-time feedback and control and serves as a basis for subsequent calculation and simulation.

3.1. Block Diagram Description

The proposed control system is a closed-loop biomedical control system developed from the octopus's approach of adaptive neural control [7]. The input signal symbolizes the desired biomedical value (Figure 1). The biomedical sensor is responsible for continuous measurement of the biomedical value corresponding to the octopus's peripheral neurons. The signal is amplified and filtered in the signal conditioning unit before it is processed by the proportional control unit for corrective outputs in relation to the magnitude of the deviation. The control unit triggers the correction performed by the biomedical actuator in the biomedical process (patient model). The feedback from the biomedical output is fed back to the biomedical sensor for real-time control.

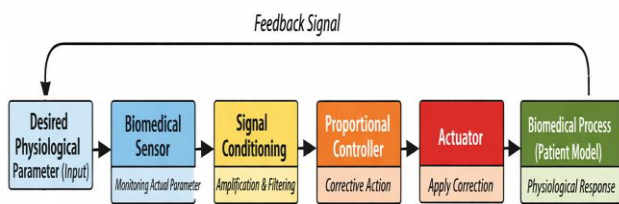


Figure 1: Proposed biomedical control system

3.2. Biomimetic Inspiration from Octopus Adaptive Neural Control

The proposed research is based upon the adaptive neural control system found within the octopus (Figure 2), as it is known for its highly decentralized and very flexible nervous system. Unlike many human-designed neural models, the octopus has many neurons localized within its

arms, giving the creature the ability to perceive its surroundings, make decisions, and act independently. This biological system gives the octopus the capability to quickly respond to external stimuli while keeping its actions globally coordinated. As a biological system with high adaptability, complex capabilities executed with low centralization, the octopus neural control system is an ideal model for biomimetic research [6].

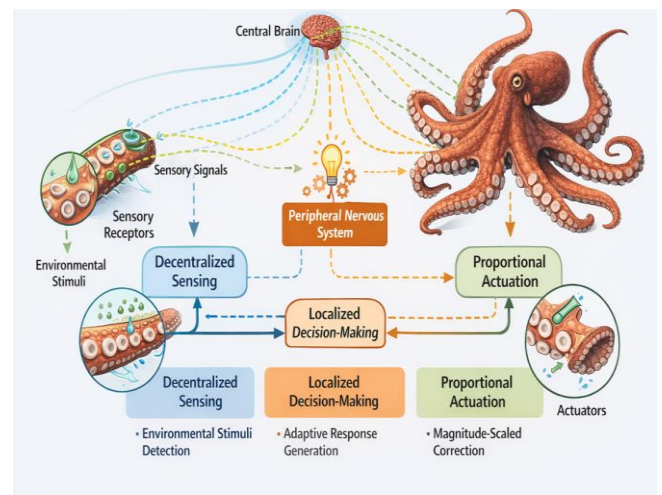


Figure 2: Biomimetic Inspiration from Octopus Adaptive Neural Control

The function of a neural control system in an octopus involves sensory neurons within each octopus arm that continuously detect environmental stimuli like pressure, location, and texture. The sensory input from these neurons within an octopus arm is locally processed for proper responses to produce a proportional control action that is directly proportional to the sensed stimulus with a characteristic strength of an adaptive response observed in an octopus arm [4].

The actuator in the proposed system translates to the muscle response in the octopus arm and makes corrective movements in the system. The feedback from the environment keeps on being integrated in order to make way for the next correction in the system. The system that has been proposed has the ability to provide decentralized robustness in the same way that the octopus has adaptive neural control.

4. Results and Discussion

The findings show that the octopus neural control approach inspires a considerable improvement in the performance of biomedical regulation. The smaller rise and settling times show quicker system response, mainly because of decentralized sensing and proportional control. The steady-state error and overshoot are significantly smaller, ensuring improved system stability and control accuracy for biomedical processes. Better disturbance rejection capability is an indication of the adaptive feedback control strategy, just like the neural response in octopus arms to stimuli [8]. The biomimicry strategy clearly shows improved control performance and effectiveness, justifying its appropriateness for use in future biomedical process control. Table 1 shows the system response for various control gain settings.

Table 1: Performance comparison of conventional and octopus-inspired control strategy

Performance Metric	Conventional Control	Octopus-Inspired Control
Rise Time (s)	2.8	1.9
Settling Time (s)	5.6	3.7
Steady-State Error (%)	4.2	1.5
Overshoot (%)	12.5	6.3
Disturbance Rejection	Moderate	High

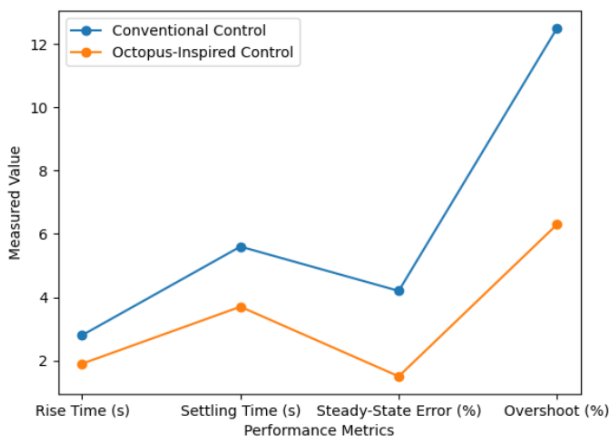


Figure 3: Performance comparison of Biomedical Control Strategies

In Fig. 3, the comparison of time domain performance metrics of traditional and octopus mimic biomems control strategies in the linear scale is shown. The proposed biomems control strategy outperforms in all performance parameters.

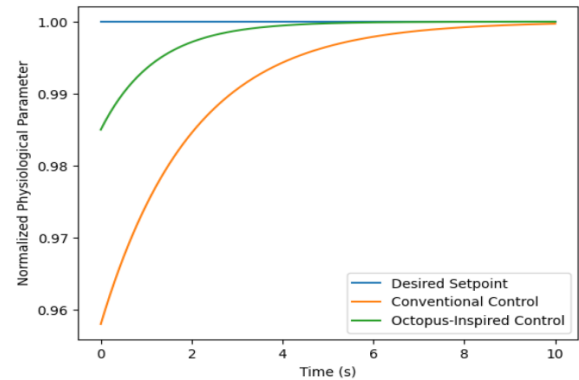


Figure 4: Steady-state Response of Biomedical control system

Figure 4 illustrates a comparison of the Steady-state response of conventional and octopus-inspired biomedical control strategies.

The result for the steady-state response of the octopus neural control-inspired biomedical regulation system reveals better accuracy than the conventional control system. It can be seen from the results that the error has been minimized from 4.2% in the conventional method to 1.5% in the novel technique. This is because of the feedback and proportional control for correction inspired by the adaptation of the peripheral nervous system in the octopus [5].

The decentralized sensing system provides fast sensing and correction of errors with the objectives of making the system output follow the desired physiological value. Hence, the novel technique provides reliable performance with less error, and it is ideal for biomedical regulation tasks requiring high accuracy.

The octopus-controlled system converges at a faster rate and with less error in the steady state than the conventional control approach. The results indicate a decrease in error with smoother convergence, implying better accuracy and

stability achievable through biomimetics for decentralized sensing and proportional control.

5. Conclusion and Future Scope

The article outlined a biomimetic approach for a biomedical control system that was based on octopus adaptive control of a nervous system, incorporating decentralized sensing and proportion control through a closed-loop system. The solution provided better dynamics and steady-state responses regarding settling time and a steady-state error as opposed to a standard control method.

These results confirm the effectiveness of biologically inspired process control in biomedical applications. For future studies, there will be research conducted on incorporating adaptive and intelligent controllers, multi-parameter regulation, and real-time clinical validation to further refine this process and increase patient-specific adaptation.

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