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The Role of Autonomous Systems and Robotics in Biochemical Engineering

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Abstract

This review considers the growing intersection of autonomous systems and robotics within the field of biochemical engineering. Automation has the potential to significantly improve the accuracy, efficiency, and capacity for high throughput and complex tasks involved in the biochemical process. This review provides evidence on the current state of the field in leveraging autonomous systems for robotic manipulation. We find that these technologies have been successfully used for applications such as wettability characterization, membrane protein management that contribute to the drug discovery process. In addition to surveying current technologies and applications, this review explores the potential next steps within this area of research. Technological advancements in robotics have generated interest and work that we believe will benefit biochemical engineering moving forward. Over the past decades, several advancements have been made in the field of robotics. Technologies such as soft materials and artificial intelligence are providing new, innovative options for robotics, increasing interest in and the relevance of this field to many applications. As a result of these innovations, robotics has become particularly pertinent to biochemical engineering, where it can be used in tandem with autonomous systems to address challenges of scale and complexity. Autonomous systems are being adapted for use in robotic manipulation and may have the ability to complement or outpace curing multi-day interruptions of practical lab work, given the right protocols. The field of drug discovery is rapidly evolving. Hence, this technology is an important contribution to biochemical engineering as well as an equally important area of study for academic researchers and industrialists.

Keywords. *Autonomous systems; micro-robots; biophysical strategies*

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I. Introduction to Biochemical Engineering and the Need for Automation

Biochemical engineering, a multidisciplinary field, plays a vital role in advancing industries by designing, developing, and optimizing bioprocesses for the cost-effective production of value-added products (Narayanan et al., 2020). These applications extend to various sectors, including environmental remediation, agriculture, pharmaceuticals, waste management, renewable chemicals, nanotechnology, biomaterials, and pulp and paper. The ultimate goal is to establish biorefineries that utilize bio-based feedstock, by-products, or waste materials to simultaneously produce fuels, power, heat, and chemical products (Boodhoo et al., 2022). Recent advancements in bioprocess development have significantly improved product titre, yields, and productivity, posing new challenges in bioreactor design and operation to ensure high productivity, process control, and safe operation (Mowbray et al., 2021; Wang et al., 2020; Isoko et al., 2024).

To address these challenges, advancements in enzyme kinetics, molecular biology, biochemistry, bioinformatics, microbiology, systems and synthetic biology, computational molecular biotechnology, bio separations, bio thermodynamics, mathematical modeling, control theory, and optimization are crucial (Zaouter et al., 2020). These require precise, reproducible, adaptable, and accurate bioprocess control and automation. For instance, microbial cellulose utilization, recombinant protein production, biodegradable plastics, and chemical synthesis by engineered microorganisms demand innovative solutions (Gao et al., 2021). Additionally, plant-wide modeling and control, real-time optimization, human-machine interfaces, cybersecurity, and economic Nonlinear Model Predictive Control (NMPC) are critical aspects to consider (Tavakoli et al., 2020; Blackiston et al., 2023).

The complexity of microbial growth and production on solid agar plates, due to substrate inhomogeneity and varied shear and mass transport, makes modeling and control challenging. Traditional ordinary differential equations often fail to accurately describe cellular processes due to high uncertainty in cellular model parameters. In response, autonomous systems and robotics offer alternatives for automating cellular processes, enabling minimal human intervention.

II. Fundamentals of Autonomous Systems and Robotics

An autonomous system consists of three main components: the hardware, the software, and the user interface (Macenski et al., 2022). Hardware is the most visible part of a robotic system, and its functionality heavily depends on sensors and actuators. In fact, sensing is crucial for intelligent behavior, as it enables feedback and reactivity (Betz et al., 2022). The importance of sensors cannot be overstated, as they facilitate the four major functions of intelligent behavior.

A control system in robotics integrates actuators and sensors to execute predefined procedures or actions when specific criteria are met (Parekh et al., 2022). This physical implementation and programming are part of a mechatronic system, which relies on the integration of mechanical, electronic, and information technology (Xie et al., 2022). The efficient working of control systems and actuators directly depends on the successful implementation of sensors. Consequently, modern robotic sensory systems are versatile, establishing connections between the physical world and computing hardware in real-time (Wang & Chortos, 2022). This enables robots to adapt to dynamically changing environments during operation. Therefore, selecting appropriate sensors and actuators is critical in designing robotic systems (Xavier et al., 2022).

2.1. Sensors and Actuators in Robotics

One of the primary challenges in robotics is enabling robots to "perceive" their environment, facilitating autonomous behavior with minimal operator intervention (Fusic S & Sugumari, 2023). This capability relies on sensors, which gather data from the environment, detecting agents, position, speed, spatial, physical, or chemical information. Conceptually, sensors permit robots to perceive the world from their internal state, comprising various pieces of information.

Sensors can be categorized based on the information they gather. For instance, visual sensors capture analog and digital visual information (Dudek et al., 2022). Tactile sensors detect force, pressure, or temperature from different areas, similar to how a blind person obtains information by touching objects. Chemical sensors transform chemical or physical quantities into electrical signals (Tayarani-Najaran & Schmuker, 2021).

Actuators, on the other hand, execute desired movements based on control choices and sensor output. The main difference between sensors and actuators lies in their action: sensors affect gathered signals, while actuators produce new signals (Raman, 2024). In biochemical engineering, actuators control biochemical processes, and their performance and choice are crucial for bioprocess management. Actuators can reach their highest potential when paired with adequately designed sensors.

Common actuators used in bioprocess control include stirring, which enhances mass transfer through impeller movement (Filippi et al., 2022). Other actuators provide information to specific plant features, such as temperature control, pH regulation, and fluid flow management (Zhang et al., 2021; Wei & Ghosh, 2022). Effective actuator design and implementation are essential for optimal bioprocess performance.

2.2. Control Systems in Autonomous Systems

A control system is the supervisory component of an autonomous system, ensuring desired performance. Open-loop control applies inputs without considering system dynamics, whereas closed-loop control utilizes feedback to enhance response, increasing accuracy and stability (Basu et al., 2023). This is achieved through feedback loops comparing actual system output and adjusting inputs accordingly. Advanced control strategies, such as Proportional-Integral-Derivative controllers, adaptive, sliding mode, and logic-based control (e.g., fuzzy logic control), have been proposed for systems requiring speed, precision, and ease of control.

Robots and automated machines mimicking sophisticated control systems have various applications, including medicine and biochemical processes (Sharma et al., 2022). Biochemical processes benefit from control systems executed in autonomously operating systems, comprising a control platform connected to embedded sensors and actuators. Real-time implementation involves decision-making processes capable of making on-the-fly decisions. Autonomous technologies, like robots and unmanned aerial vehicles, operate in nonlinear, time-variant, and often hostile dynamic environments. Similarly, biochemical processes are nonlinear, time-variant, and dynamic, requiring robust and adaptive control systems to mitigate disruptions, flaws, or process irregularities (Zhang et al., 2021).

In biochemical processes, control systems must be dynamic and adaptable to various operating modes. These systems can adapt quickly to change and disturbances due to the use of complex control approaches. The use of advanced instrumental control lowers variability, increases reliability and enhances productivity, in biochemical reactions.

III. Applications of Autonomous Systems and Robotics in Biochemical Engineering

Autonomous systems and robots are vital in biochemical engineering to perform the reproducible measurements instead of human hands to produce novel biochemical findings (Abolhasani & Kumacheva, 2023). Automation makes it easier to optimize bioprocessing including fermentation and controlling of process, scale-up and enhances productivity, yield and reliability. Other uses include the handling of mammalian cell culture and analytical testing, and downstream processing. Drug discovery in HTS has the capability of quickly testing thousands or millions of chemical compounds for the efficacy of biomolecules (Martin et al., 2023).

Motors and computational algorithms direct robots' movements, and when aligned, create discrete systems (Lockhart et al., 2023). The application of this technology in biochemical engineering is referred to as automation, or integration of automation and robotics. Robotic/autonomous systems can provide researchers with the needed level of control and measurements of biochemical reactions to facilitate enhancements of processes and products (Bultelle et al., 2024). Such robots are not easy to design and have been several case studies that outline some of the strengths and weakness of embracing automation and robotics in biochemical engineering research.

The following cases show how the concepts of the autonomous system and robotics are providing breakthrough solutions in the biochemical engineering domain, ranging from bioprocess optimization to drug discovery (Rapp et al., 2024). Hence through automation and robotics, the researchers are able to eradicate bottlenecks that come with explorative experimentation while disseminating new findings.

3.1. Bioprocess Monitoring and Control

In process engineering, continuous supervision of bioprocesses is essential for the management of hydrochemical conditions promoting biological activities (Duong-Trung et al., 2023). Biochemical engineering is meant to study the high order of cellular functions and design equations that would describe various cell functions (Rösner et al., 2022). Microorganisms require regulating parameters for biochemical cell activities like growth, enzyme synthesis, microbial metabolism, etc. (Havlik et al., 2022). These processes demand close regulation of biochemical devices and especially for varying values (Narayanan et al., 2020). Robotization and automatization ensure high throughput, improving system maintenance as well (Mondal et al., 2023).

End-of-the-year figures point to errors and decisions making problems and major concerns and differences in outcomes (Reardon, 2021). Monitoring requires real-time operations in order and specific log files for process tweaking (Wasalathanthri et al., 2020). Some technology tendencies measure and manage biochemical processes in terms of the industry, such as pH or temperature to manage the quality of the product (Luo et al., 2021).

Logical systems for quantifying finished products and closed loop fine-tuning also requires to be kept up. Newer approaches in polarity control systems have enhanced the monitoring as well as tracking potential in monitoring and tracking applications, enhancing the quality of the product (Duong-Trung et al., 2023). These are real-time applications of technological growth which the future expansions will require for large-scale operations (Narayanan et al., 2020).

The bioprocess is continuously observed and regulated through logical control of its chemical, physical and biochemical reactions (Rösner et al., 2022). Include, reagents, temperature, pressure, pH and diffusion characteristics of the system to be used. Mass biochemical measures major on genetic content assertiveness and availability (Mondal et al., 2023).

Microbial perturbations are defined by small molecules including nutrients, proteins and metabolites (Duong-Trung et al., 2023). Bioprocess equations represent relationships among hydrochemical conditions, enabling monitoring and control of biochemical dynamics based on process variables (Rösner et al., 2022). For instance, ethanol production requires optimal pH levels; deviations can damage enzymes and slow production (Reardon, 2021). Fixing monitoring systems to quality variables maintains consistent product formation rates (Luo et al., 2021).

3.2. High-Throughput Screening in Drug Discovery

The early stages of drug discovery involve large-scale screening of chemical compounds to modulate disease targets at the molecular or cellular level. Traditionally, biologists manually conducted experimental procedures, but human variability introduced "biologically insignificant" noise into the data (Pyzer-Knapp et al., 2022). High-throughput screening (HTS) addresses this issue, utilizing robotics, data processing software, liquid-handling devices, and sensitive detectors to rapidly conduct biological or biochemical experiments (Schilling et al., 2023). HTS enables screening of thousands to billions of compounds per day, accelerating the search for new drug bioactivity.

Robotic control is the key ingredient in HTS, automating assay steps such as dispensing, incubating, and mixing (Mahjour et al., 2023). This significantly speeds up the search for new drugs. For instance, where the robotic methods could perform 1,536 assays in one day with 3,840 samples, the manual methods allow only 2-3 samples per daily analysis for biologists (Schilling et al., 2023). Robotic procedures have made it easy to handle liquids which makes it fast for scientists to assess drug candidates.

Data management is also important in drug discovery processes also as it is in any other major processes. As big image data continue to gain relevance, writings and signaling are employed to identify faint motions and search for diseases (Rapp et al., 2024). Such data allows making drug decisions regarding health more individual, open, and financially beneficial. The use of automation in imaging and data analysis help in speeding up the drug discovery processes (Duong-Trung et al., 2023).

IV. Challenges and Future Directions in the Field

However, several issues need addressing in integrated, unsupervised systems to enable implementation within biochemical laboratories and antibiotic production (Seifrid et al., 2022). The presented issues discussed below are critical to the adoption of commercial robotic systems in biochemical facilities: A major concern is that most commercial robotic systems may need significant adaptations to function optimally in biochemical environments. Further, standard software and laboratory instruments integration can be hindered due to poor standardized protocols from software vendors (Dixon et al., 2021). Robotics could go some way in doing this with standardized software and equipment packages.

Another main issue is the need to create fully autonomous systems, which complicates the design of the system. Such a combination could be assisted by collaborating systems with different knowledge and methods in terms of this complexity (Fottner et al., 2021). Nevertheless, it is possible to achieve effective collaboration between specialists in robotics science and biochemical researchers to address these questions. Concerning the ethical implications of fully autonomous robots with personnel in laboratory settings, there is the following: First, autoethgraph is a completely automated robot system, and such issues as safety and flexibility are uncertain.

Robots need to be tested widely in the modern chemistry laboratory with materials that are harmless, and bench scale or flow chemistry machining (Zaouter et al., 2020). Specifically, progress in the field of machine learning and artificial intelligence is also required to fully realize autonomous systems in biochemical engineering at the next step. At the moment, such systems are still in their infancy and have only just begun simple integration into flow chemistry (Seifrid et al., 2022).

For such obstacles, further emphasis on cross-disciplinary collaborations and physically safe laboratory environments with complete robotic autonomy is required (Duong et al., 2020). The outlook for this type of technology and process dictates further planning and potential progress in more discreet measures within the automated systems.

4.1. Ethical and Safety Concerns in Autonomous Systems

In biochemical engineering, the use of artificial intelligence and AS is expressly applicable, but many ethical and safety issues arise concerning decision-making and action processes (Jedličková, 2024). Moral responsibilities are a factor that comes in to play the most when automation is present in a process. Hence, it is important to set-out codes of conduct and realistic policies for responsible innovation that could and should guarantee that the robots would behave responsibly and appropriately in laboratories. Future work seeks to create measurable ethical practices and present comprehensive safety evaluations of continually emerging robotics and other autonomic systems (Mezgár & Váncza, 2022).

Data privacy, transparency, and accountability present other problems to the use of AS in chemical engineering (Wang et al., 2021). To respond to these issues, new certifications guarantee engineers deal with AS properly respecting ethical, legal, and skilled norms. They also prescribe how precautionary measures apply to autonomous systems.

General safety is the main consideration while applying AS in laboratory and industrial environments, K (Shu et al., 2023). While risk Eengineering perspectives aim at managing potentially dangerous situations, safety involves farther shield of people, buildings, properties, other structures, and hazardous substances from AS-related incidents and adversarial use. Procedural, physical, and technical measures mitigate AS obligations and characteristics. Each application must assess necessary specifications, risks, and hazard scenarios.

Ensuring error-tolerant architectural approaches requires compliance with safety rules, especially when AS interacts with objects and components (Kato et al., 2023). Awareness, safety training, and procedural facilitations are vital to saving lives in emergency situations. Human-controlled and AS-enabled emergency shutdowns rely on embedded functional feedback, informing lab workers about potential dangers (Li et al., 2022). In its absence, safety protocols and technical facilitations become crucial.

V. Conclusion

Autonomous systems and robotics are technologies that excel at laborious tasks requiring high precision and reliability. The precarious nature of biochemical Engineering renders these systems ideal candidates for implementation. The integration of assistive and autonomous robots has been demonstrated to lead to a significant enhancement in the efficiency, precision, and reliability of a range of tasks, which is necessary to eliminate human error and ensure continuous operation when self-optimization is not feasible. The accuracy of existing vision and force sensors further demonstrates the potential for research leading to such implementation in new and existing laboratories. Development in micro and nanorobotics has the potential to further advance the biological applications of autonomous systems and should continue to be researched to produce reliable systems. The general trend in automation and robotics is towards increased reliability and sophistication, while becoming smaller, cheaper, and more widely available. Capitalizing on these technological improvements will require extensive interdisciplinary research investment to develop autonomous systems and robotics tailored for specialized biochemical task functions. The ability to develop, engineer, and build such systems must be informed by ongoing collaboration between engineers, scientists, and ethicists. These partnerships will be crucial in communicating advances and exploiting inherent opportunities. The education of future professionals with respect to automation and robotics is vital to continue the development and implementation of such systems. System modularity and the ability to easily switch components will ensure that future development in autonomous systems can be integrated into existing technology, allowing the field to evolve as technology continues to advance. In conclusion, automation and robotic systems in biochemical processes have the potential to result in a highly efficient number of repetitive tasks and transitions to take place over extended periods of time. In addressing the identified challenges, the field of biochemical Engineering is poised to direct the development of these systems, which will greatly increase the robustness of the workflow by preventing a wide range of unintended events. The implications of growing into an autonomous robotic process in the field of biochemical engineering, and indeed all life sciences, are vast. Being on the precipice of a fully automated biological laboratory is equal parts exhilarating and thought provoking. It is our recommendation to all stakeholders to engage in the discussion regarding the phase-out of human intervention, keeping in mind the historic analogues that may be helpful in building the path forward. This may not only make this transition smooth but also result in a safer and more ethically sound future.

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