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AI-DRIVEN MULTI-ARM ROBOTIC PLATFORM FOR AUTONOMOUS BIOREACTOR SERVICING IN SUSTAINABLE SPACE LIFE SUPPORT SYSTEMS

Abstract

Long-duration space missions demand life support systems that are both reliable and efficient to safeguard crew health and ensure habitat sustainability. At the core of these systems are closed-loop bioreactors that convert carbon dioxide into oxygen while cultivating algae or bacteria to generate supplemental food sources. In this research, we propose developing an advanced multi-arm robotic platform for the autonomous servicing of bioreactors—optimizing life support operations with minimal crew intervention. Our investigation centers on two primary design approaches. The first employs a system with multiple articulated arms equipped with specialized end-effectors engineered for precise fluid line coupling, sampling port management, and micro-syringe assemblies for nutrient injection and microbial modulation. The second approach utilizes a collection of task-specific end-of-arm tools with tool changers, enabling efficient and precise reconfigurations while integrating process-specific sensors. Continuous real-time monitoring is essential for bioreactor processes. Sensors—including pH meters that gauge acidity to maintain biochemical balance, dissolved oxygen sensors that monitor the oxygen levels vital for microbial activity, and turbidity detectors that assess culture density—collect critical data. Decision-making is driven by the Proximal Policy Optimization (PPO) reinforcement learning algorithm, which dynamically adjusts fluid flow rates, nutrient delivery, and stirring patterns. This algorithm deftly balances the exploration of new parameter settings with the exploitation of established optimal conditions to maximize bioreactor efficiency. To further enhance system resilience, an anomaly detection network—trained on extensive historical bioreactor data—will proactively identify irregularities such as shifts in growth patterns or sensor anomalies before they escalate into major issues, thereby safeguarding culture integrity. The multi-arm configuration permits simultaneous, independent servicing tasks that substantially reduce maintenance time and crew effort. In contrast, while the multiple end-of-arm tooling design facilitates detailed data collection and precise process control, it may incur increased cycle times and higher costs. Custom end-effectors ensure seamless interactions with bioreactor components such as fluid lines, sampling ports, and injection points, enabling operations that are both precise and efficient. This autonomous system promises significant benefits for sustainable space life support: reduced astronaut workload, lower resource consumption, and uninterrupted bioreactor functionality. By optimizing bioreactor performance, the system enhances mission sustainability and longevity, aligning with the goals of establishing regenerative ecosystems in extraterrestrial environments. Ultimately, it lays a robust foundation for scalable, adaptable technologies that will be indispensable for future human exploration and habitation beyond Earth.

Keywords: Autonomous Robotic, Life Support Systems, Bioreactor Servicing, Multi-Arm Platforms, Deep Reinforcement Learning, Sustainable Space Habitats, AI-Driven Automation.