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Safety-Embedded Control Architecture for 3-DOF Lifts of Mobile Manipulators in Nuclear Maintenance Tasks

Hyeokbeom Kwon[a,b], Jinyi Lee[b], Jongwon Park[a,b*]
[a]*University of Science & Technology, Gajeong-ro 217, Yuseong-gu, Daejeon, Republic of Korea*
[b]*Korea Atomic Energy Research Institute, Daedeok-daero 989-111, Yuseong-gu, Daejeon, 04535, Republic of Korea*
[*]*Corresponding Author: jwpark@kaeri.re.kr*

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1. Introduction

Mobile manipulators deployed in nuclear power plants are essential for remote maintenance, inspection, and decommissioning tasks in high-radiation environments. [1] To effectively interact with control panels, valves, and components at varying elevations, these robotic systems frequently employ multi-degree-of-freedom (DOF) lift mechanisms. The reliability of these lifts is paramount; any mechanical or software failure could result in the dropping of hazardous materials or damage to critical infrastructure.

This paper proposes a safety-embedded control architecture for a hydraulically actuated 3-DOF lift system [2]. The controller incorporates asymmetric error handling, non-linear kinematic conversions, and a multi-tiered safety logic framework based on real-time fluid pressure monitoring. Furthermore, we address the systemic challenges of hardware-in-the-loop concurrency, ensuring robust digital-to-analog communication in multiprocessing environments.

2. Proposed Control Architecture

The control system is designed to govern the vertical positioning of the manipulator through three primary articulation points: the ankle, knee, and hip joints. The architecture calculates joint-level efforts based on trajectory profiles governed by predefined maximum velocity, acceleration, and deceleration limits.

2.1. Kinematic Conversion and Asymmetric Control

Actuation of the lift joints is driven by linear cylinders. Therefore, angular joint position references must be mapped to linear actuator stroke lengths. The controller employs a trigonometric length converter derived from the law of cosines to dynamically calculate the required linear displacement for each joint based on its base length and rotational pivot offsets:

$$l = \sqrt{l_{base}^2 + l_{rot}^2 - 2 l_{base} l_{rot} \cos(\theta + \theta_0)}$$

Where l is the actuator length, l_{base} and l_{rot} are the geometric lengths of the linkage, θ is the joint angle, and θ_0 is the geometric offset.

Once the reference lengths are established, the system employs a proportional-integral-derivative (PID) control strategy. Due to the asymmetric effects of gravity on the heavy lift mechanism (e.g., lifting requires overcoming gravity; while lowering is assisted by it), the controller dynamically schedules its gains. Positive tracking errors and negative tracking errors trigger separate sets of tuning parameters, ensuring smooth and stable motion in both directions without over-actuation.

2.2. Concurrency and Hardware Interface

High-level control systems often utilize multiprocessing to maintain strict control loop frequencies while handling computationally heavy tasks. However, passing hardware communication interfaces across process boundaries can corrupt low-level serial states. To ensure robust performance, the proposed architecture isolates the initialization of the digital-to-analog voltage output devices. The hardware connections are strictly established only after the child control processes are spawned. This prevents USB communication state corruption and guarantees uninterrupted transmission of analog voltage commands to the proportional valves governing the lift.

3. Safety-Embedded Logic

In nuclear applications, hardware protection must be embedded directly into the lowest level of the software architecture. The lift's structural integrity heavily relies on maintaining adequate fluid pressure. The controller integrates an Exponential Moving Average (EMA) filter to smooth incoming raw pressure data, mitigating the risk of false-positive safety triggers caused by sensor noise.

The safety logic evaluates the filtered pressure against two distinct thresholds:

- **Soft Limit Interlock:** If the system pressure drops below a soft operational threshold (e.g., 60 bar), the controller initiates a proportional reduction of all actuation commands. The scaling factor is calculated linearly based on how far the pressure has dropped toward the critical failure point. This gracefully degrades performance, preventing sudden jerky halts while warning the operator.

- **Hard Limit Cutoff:** If the pressure falls below a critical minimum boundary (e.g., 45 bar), a hard safety interlock is triggered, instantly zeroing all output commands to freeze the lift in place and prevent a catastrophic collapse. To prevent rapid oscillation (chattering) of the valves if the pressure fluctuates exactly around the threshold, a recovery hysteresis band is enforced. The system will not release the hard interlock until the pressure has comfortably exceeded the threshold plus the defined band.

Additionally, the control state continuously monitors sensor read validity and main power states, instantly zeroing outputs if telemetry is lost.

4. Conclusion

The proposed control architecture provides a highly resilient and accurate positioning system for 3-DOF lift mechanisms on mobile manipulators. By combining asymmetric PID tuning, rigorous kinematic mapping, and a multi-tiered, pressure-based safety interlock, the system ensures stable operation even under varying load conditions and hardware anomalies. Future work will explore the integration of adaptive feed-forward compensation to further minimize tracking errors during high-speed vertical extensions.

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