

INTISARI

Perkembangan teknologi teleoperasi pada alat berat seperti ekskavator sangat penting untuk memitigasi risiko keselamatan di lingkungan kerja yang berbahaya. Namun, hilangnya umpan balik fisik (*sensory deprivation*) dan adanya latensi komunikasi sering kali memicu osilasi gerak dan kesalahan kendali oleh operator. Simulator pelatihan dengan fidelitas tinggi di pasaran memiliki harga yang sangat mahal, sementara simulator berbasis mesin permainan (*game engine*) umumnya kurang akurat secara fisika. Penelitian ini bertujuan untuk mengembangkan purwarupa simulator teleoperasi ekskavator berbasis Digital Twin menggunakan MATLAB Simscape Multibody, yang diintegrasikan dengan stasiun antarmuka fisik berbasis mikrokontroler ESP32 dan joystick industrial. Algoritma kendali Proportional-Integral-Derivative (PID) yang dikombinasikan dengan pemodelan fungsi alih (transfer function) diterapkan untuk meredam osilasi akibat momen inersia yang besar dan beban gravitasi pada lengan ekskavator. Lima protokol komunikasi dievaluasi untuk menemukan kinerja terbaik, meliputi Serial USB, Bluetooth SPP, WiFi TCP/IP, WiFi UDP SoftAP, dan MQTT Cloud. Hasil pengujian menunjukkan bahwa komunikasi WiFi UDP SoftAP menghasilkan kinerja nirkabel paling optimal untuk simulasi jarak dekat secara mandiri (standalone), dengan pencapaian latensi rata-rata 4 ms dan packet loss 0%. Selain itu, implementasi kendali lingkaran tertutup PID terbukti mampu melacak sinyal referensi masukan secara dinamis dan presisi tanpa adanya overshoot, serta menjaga stabilitas gerak model secara seketika (real-time). Secara keseluruhan, simulator yang dikembangkan ini berhasil mereplikasi batasan mekanis ruang gerak dan waktu tempuh (*cycle time*) aktuator yang identik dengan spesifikasi alat berat riil, sehingga menjadikannya media pelatihan teleoperasi yang realistis, stabil, responsif, dan hemat biaya.

Kata kunci: Teleoperasi, *Digital Twin*, Ekskavator, Kendali PID, *Simscape Multibody*, Latensi Komunikasi.

ABSTRACT

The development of teleoperation technology in heavy equipment such as excavators is crucial to mitigate safety risks in hazardous work environments. However, the loss of physical feedback (sensory deprivation) and communication latency often trigger motion oscillations and control errors by operators. High-fidelity commercial training simulators are extremely expensive, whereas game engine-based simulators generally lack physical accuracy. This study aims to develop a prototype of an excavator teleoperation simulator based on a Digital Twin using MATLAB Simscape Multibody, integrated with an ESP32 microcontroller-based physical interface station and industrial joysticks. A Proportional-Integral-Derivative (PID) control algorithm combined with a transfer function modeling is applied to dampen oscillations caused by the large moment of inertia and gravitational load on the excavator's arm. Five communication protocols were evaluated to determine the best performance: Serial USB, Bluetooth SPP, WiFi TCP/IP, WiFi UDP SoftAP, and MQTT Cloud. The test results demonstrate that WiFi UDP SoftAP communication yields the most optimal wireless performance for local standalone simulation, achieving an average latency of 4 ms and 0% packet loss. Furthermore, the implementation of closed-loop PID control is proven to dynamically and precisely track the input reference signals without any overshoot, maintaining the model's motion stability in real-time. Overall, the developed simulator successfully replicates the mechanical workspace limits and actuator cycle time identically to real heavy equipment specifications, establishing it as a realistic, stable, responsive, and cost-effective teleoperation training medium.

Keywords: *Teleoperation, Digital Twin, Excavator, PID Control, Simscape Multibody, Communication Latency.*