Remotely Controlled Excavator System with Enhanced Safety for Built Environments

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***Abstract*—Remotely operated excavators enhance safety, productivity, and efficiency in construction environments. This paper introduces a new system design aimed at improving the remote control of excavators. The setup utilizes the ROS2 middleware framework on a 5G network, with simplified on-site infrastructure requirements, achieving low latency in communication between master and slave components. Another notable aspect of this system is its safety module, which includes toppling and collision detection. The collision detection is engineered to identify general obstacles rather than specific objects or excavators, using active pose measurement.Results presented in this paper validate the system's efficacy in network analysis, collision tests, and toppling detection. The proposed design contributes to improved performance and safety standards, providing valuable insights for further research and development in this field.**

***Index Terms*—Teleoperation , Built-environments, Collision detection, Toppling detection, Operator safety, Remotely Controlled Excavator**

I. INTRODUCTION

Excavators are among the most widely used and versatile machines in the construction industry [1]. However, accidents involving machine toppling, especially on uneven terrain or in hazardous environments like landfills containing flammable gases, pose significant risks to operators [2] [3]. Teleoperation of the excavator can help reduce these risks by decreasing the need for human proximity to the machine [4]. By upgrading the machine with sensing equipment and safety sensors, the remote operator can maneuver the machine from a teleoperation command center to enhance safety.

However, the presence of communication delays directly affect the operator's control precision, emphasizing the need for a network with low latency and high bandwidth. In previous studies both 5G [5] and WiFi networks have been demonstrated to showcase a low-latency teleoperation. 5G network offering a minimum latency of $1\ \mathrm{ms}$ and a speed of up to $10\ \mathrm{Gbps}$ was reported in [6], with a range around $500\ \mathrm{m}$. However, 5G signal is easily blocked by obstacles such as trees or walls. On the other hand, WiFi 6 [7] offers $9.6\ \mathrm{Gbps}$ speed and a latency of 20 ms in an maximum range of $50 - 100\ \mathrm{m}$ per router in point to multipoint configuration. The range can be extended in outdoor to a few kilometres by using directional antennas (with line-of-sight) that offer a better penetration through obstacles than the 5G network. Both approaches seem to have their pros and cons and the choice of network selection depends on the use cases.

Previous studies show the use of ROS (Robot Operating System) middleware in relation to heavy machines or excavators [8]. Excavator companies such as Volvo are investing in ApexAI, which is developing a ROS-based mobility system for their construction equipment [9]. Meanwhile, Komatsu is using a fleet of UAVs controlled through ROS to update construction progress [10]. For smooth operation, real-time feedback from sensors, especially visual sources, is crucial. One key aspect of teleoperating excavators is ensuring robust safety systems [11]. To enhance the safety of remote-controlled excavators, [12] proposes a collision avoidance approach that targets obstacles, specifically when one excavator is in close proximity to another.

The paper introduces a new system design aimed at improving the remote control of excavators, coupled with a low-latency communication infrastructure. Using the ROS2 middleware framework on a 5G network, this system achieves low latency in communication between master and slave components. A notable aspect of this system is its safety module, which includes toppling and collision detection. The collision detection is engineered to identify general obstacles rather than specific objects or excavators, using active pose measurement.This feature allows for precise safety control and individual joint movement in real-time, avoiding the need to stop the entire excavator. By enabling remote operation of excavator machinery while effectively mitigating safety hazards such as collisions and toppling , this system significantly elevates safety standards.

The remaining paper is structured as follows. Section II presents the overall system architecture and description of its respective components. The results for network analysis, collision test, toppling tests and teleoperation delay are discussed in section III. Lastly, in section IV conclusion and future work for further enhancement of the system are presented.

II. System Architecture and Components

The system architecture of the remote-controlled excavator, illustrated in Figure 1, includes essential subsystems that collaborate to enable smooth operation, safety and communication. The communication between the teleoperation master and excavator slave is carried out through the middleware layer. The safety system resides in the excavator side, and responds to the information from the safety sensors in excavator and also shares relevant information to the middleware side. To enhance situational awareness and mitigate risks, the excavator is equipped with LiDAR sensors and camera views, configured to detect any potential blind spots during operation. Detailed explanation of the sub systems is provided in the subsequent sections.

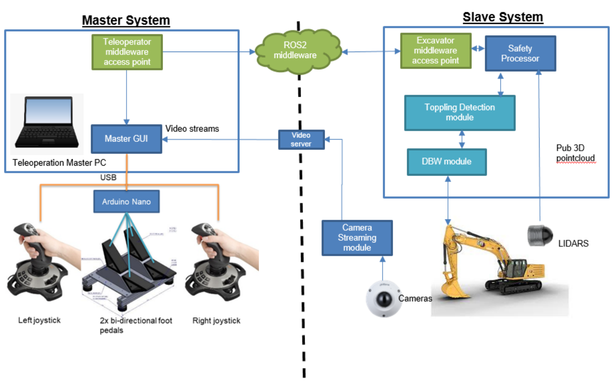
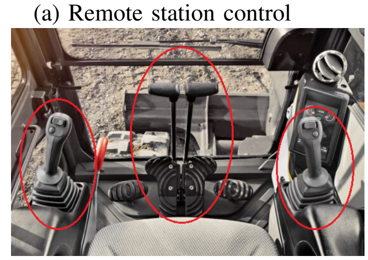


Fig. 1: System Architecture

(a) Remote station control



(b) In cabin control

(c) Remote station GUI design

Fig. 2: Comparison of in cabin control with remote station control

A. Teleoperation Command Centre

The teleoperation command centre serves as a central control hub where the remote operator receives real-time sensor feedback and issues commands to teleoperate the excavator machine. Through a seamless streaming of video and sensor data from each excavator, the command centre provides the operator with comprehensive situational awareness of the excavator's surroundings. This real-time information empowers the remote operator to make responsive decisions and effectively control the low-level bucket and track movements of the excavator.

The control inputs of the remote command centre are designed to mimic the controls inside a typical excavator cabin. Fig. 2a showcases the control interface, consisting of left and right joysticks for cabin, boom, stick, and bucket controls, as well as bi-directional foot pedals for track control. This familiar control layout as in Fig. 2b inside a typical excavator enables the operator to easily maneuver and control the excavator remotely, ensuring a seamless teleoperation experience.

The GUI (Graphical User Interface) design, as depicted in Fig. 2c, further improves the usability of the command centre. Depending on the option of the remote operator, it provides the freedom to switch between various excavator control standards, such as ISO controls (ISO 10968) and SAE controls (SAE J1814). Additionally, the GUI displays any safety alarms or warnings sent by the excavator system, allowing the operator to react quickly and change the excavator's joint movements for improved safety.

B. Middleware and Communication

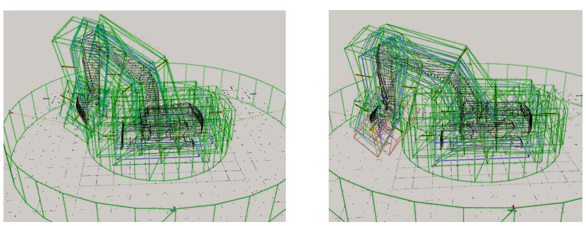
The middleware manages the transmission of messages between components of the teleoperation system using the open-source ROS 2 framework, which operates on top of a DDS. The middleware solution consists of a middleware server and access point nodes for each component of the teleoperation system. The middleware server serves as the central control hub, and allows the assignment of connections between teleoperator, excavator, and other system components. The access point nodes, associated with each teleoperator or excavator, receive commands from the middleware and enable the reception of the correct messages for their respective entities. To avoid network congestion, cameras are streamed through a different layer and not handled through middleware.

C. Wireless Network

The remote-controlled excavator system utilises public 5G connectivity enabled with enterprise-based SIMs to establish seamless communication between the teleoperation command center and excavator system [13]. Contrary to Wi-Fi connectivity, which necessitates additional setup of on-site IT infrastructure and subscriptions for internet-based solutions with virtual private network, public 5G connectivity with a standard telco back-haul does not require substantial local infrastructure. As a result, the overall on-site infrastructure requirements is reduced and the site-to-site communication setup is simplified.

D. Safety System

Safety system consists of sensors and safety processor installed on the excavator to provide updated information about the current state of the excavator. Sensors, including GNSS and IMUs of excavator 3D guidance system, cameras and 3D LiDARs, provide both the sensing feedback for the command control and certain safety features (collision detection, toppling detection). The GUI at the command centre has an indicator of the safety status.



(a) No collision detected (b) Collision detected

Fig. 3: Visualization of collision detection module on Excavator

1) Collision Detection Module: Fig. 3 shows the collision detection module used for this teleoperation system as displayed on ROS Robot Visualizer (RVIZ). This module utilizes at least one range-sensor such as LiDAR, sonar, RGBD camera to capture the 3D pointcloud of the surrounding environment. The main function is to prevent unwanted collision in a dynamic environment as operators have limited view and blind spots during remote teleoperation. The module will validate if an obstacle has entered the predefined 3D safety regions (drawn in green in Fig. 3); and when triggered, it will identify which of the multiple joints and their direction of joint motion to block off to prevent collision with the detected obstacle. Fig. 3a shows the safety system running without any obstacles, whereas Fig. 3b shows the triggered safety region at the bucket in red when the operator attempts to push into the ground.

There are different safety profiles set in place for the operator to toggle between depending on the use-case scenarios. One of the profiles includes a digging mode which only the safety region at the bucket is removed, while still keeping the rest of the safety check enabled. This enables the bucket to contact with the ground during digging.

2) Toppling Detection Module: A software module was developed to estimate the likelihood of an excavator toppling over during operation. The software module does this by computing the dynamic balance of the excavator at a given moment in time using available sensor inputs. The dynamic balance of the excavator is computed using the Zero-Moment Point (ZMP) approach. The ZMP is a point on the plane supporting the excavator's base about which no overturning moments are present. At the ZMP, only a reaction force and sliding moment is present to support the dynamics of the excavator. The toppling condition is then defined as follows:

$$\mu_s = \min\left(\frac{d_x - |0'P_{Zx}|}{d_x}, \frac{d_y - |0'P_{Zy}|}{d_y}\right) \quad (1)$$

Where d_x and d_y are the dimensions of the excavator's footprints, P_{Zx} and P_{Zy} represent the coordinates of the ZMP. In the event that μ_s is below 0, then the ZMP lies outside the excavator's footprint which would mean that there is a presence of an overturning moment.

III. Results and Analysis

To validate the system design, first a simulation study was done in Vortex Studio with an excavation environment set up with a generic 36 tonne, 270 hp track based excavator model. The excavator model was configured with the camera view and sensors to validate the safety system design and provide a visual indication for optimum view or coverage respectively. Experimental validation entailed the development and rigorous testing of the proposed system design (middleware, 5G communications, safety systems, remote teleoperation station) in a physical excavator prototype customized for teleoperation: the CAT 320 20-tonne Electro-hydraulic Excavator, specifically retrofitted to enable remote teleoperation as depicted in Fig. 4. The excavator was equipped with 5 LiDAR sensors and 5 cameras for safety, alongside a Drive-by-Wire system

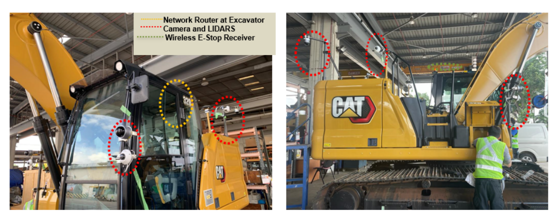


Fig. 4: Retrofitted Excavator for teleoperation

A. Collision Test

To evaluate the safety collision system, a series of collision tests were set up in simulation study as shown in Fig. 5. In order to quantify the effectiveness of our directional safety module, each individual test will attempt to collide the excavator's bucket end-effector into the wall through teleoperation of a different singular joint motion each. The safety module will trigger by lowering its safety velocity factor to slow down before stopping the operators' velocity command for that specific joint motion. In all tests, the teleoperator will continue to attempt moving the excavator into the wall.

The plot of a single test using the cabin counter-clockwise (CCW) rotational motion is shown on Fig. 6. Fig. 6a shows the tracking data for the full time frame of the test. It includes the bucket tip velocity as the excavator moves, the command velocity from the teleoperator, and the joint angle of the cabin yaw motion. The distance refers to the euclidean distance of the bucket tip to the wall. The safety factor is a scaling factor used by our safety module to scale down the motion of the joint. A safety factor of 0 means complete stop. Fig. 6b illustrates the same test with shorter time period 11.40 sec to 12.40 sec, when the safety is triggered at 11.80 sec as the wall is detected.

The effectiveness is gauged with the response time and safety stopping distance. The response time is defined here as the time required for the bucket velocity to become zero after the safety is triggered; and safety stopping distance refers to the final distance that the excavator bucket comes to a halt away from the obstacle.

For tests with driving of the excavator track, one of the test data is displayed as shown in Fig. 7a and also a smaller time period as shown in Fig. 7b. For the tracks, the velocity is larger and the tests start further away from the wall. When the excavator gets closer to the wall, the safety factor reduces the velocity by half before finally coming to complete halt as the wall gets close. The distance plot took a few milliseconds after to settle due to sliding and inertia behaviours of the simulator's physics.

The Table I lists the results obtained from the simulation performed on Fig. 5. In all 21 obtained results, the safety module prevented the excavator from colliding with the obstacle.

The safety stopping distance is affected by the preset distance of the 3D safety region, and can be adjusted. Hence, we recorded the error distance which refers to the additional distance required after safety is triggered for the excavator to stop completely. This error is also affected by excavator's inertia and velocity it is previously traveling at, Fig. 6a.

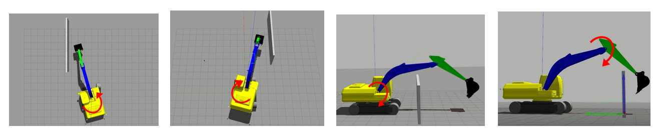
From the results analysis, the safety distance showed that for larger range motions like cabin swing, more buffer distance were given, allowing the arm to stay at least 2 m away from obstacles. As for smaller range motion like bucket curl out, we have to position excavator starting pose very close to wall for it to trigger using just the rotational axis, hence the small safety distance of 0.46 m. The error distance is an average of 0.226 m due to sliding, inertia and response time, and should be considered when placing buffer distance to safety regions.

For track data analysis, there is a small inconsistency due to inexperience of the teleoperator with foot pedal input. The excavator did not fully drive straight unless both left and right track pedals have equal amount of force applied. By average, the driving safety response time is fast within 0.1 s , but the inertia and sliding of the track caused a larger safety distance error of 0.559 m.

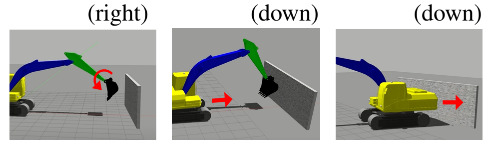
Overall, the tests showed the safety module capabilities to prevent collision with the wall, and keeping about 1 m away from obstacle with a good response time.

TABLE I: Results table for Collision test in Gazebo Simulation

Joint	Test	Response Time(s)	Safety Distance(m)	Error Distance(m)
3*Cabin Left	1	0.100	1.936	0.211
	2	0.140	1.943	0.204
	3	0.240	1.929	0.218
3*Cabin Right	1	0.200	1.936	0.211
	2	0.159	1.910	0.237
	3	0.160	1.915	0.232
3*Boom Down	1	0.120	0.743	0.257
	2	0.280	0.726	0.275
	3	0.140	0.757	0.243
3*Stick Down	1	0.180	0.749	0.251
	2	0.120	0.753	0.247
	3	0.160	0.751	0.250
3*Bucket Out	1	0.160	0.464	0.186
	2	0.180	0.471	0.178
	3	0.280	0.464	0.186
			Average arm response time = 0.188 s	
			Average arm safety distance = 1.163 m	
			Average arm error distance = 0.226 m	
3*Track Forward	1	0.100	0.683	0.317
	2	0.040	0.854	0.146
	3	0.060	0.563	0.438
3*Track Reverse	1	0.060	1.533	0.467
	2	0.079	0.909	1.097
	3	0.020	1.101	0.899
			Average track response time = 0.059 s	
			Average track safety distance = 0.941 m	
			Average track error distance = 0.559 m	



(a) Cabin CCW (left) (b) Cabin CW (right) (c) Boom CCW (down) (d) Stick CCW (down)



(e) Bucket CW (out) (f) Track Forward (g) Track Reverse

Fig. 5: Collision test performed on Gazebo Simulation

B. Toppling Test

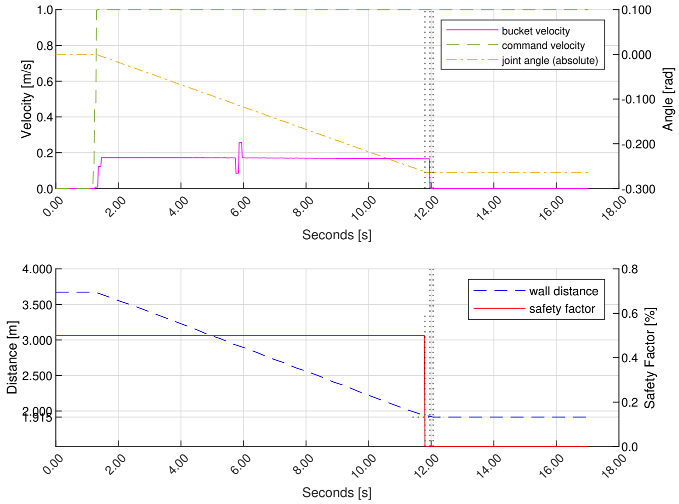
A simple simulation was done to test the toppling software. Two trajectories were created where the first trajectory is gentle and the other a more aggressive manoeuvre. The movement of the corresponding ZMP is shown in Fig. 8.

From the Fig. 9, it can be concluded that the fast trajectory on the right leads to dynamic imbalance as the zero-moment point moves outside the support polygon compared to the gentler trajectory on the left.

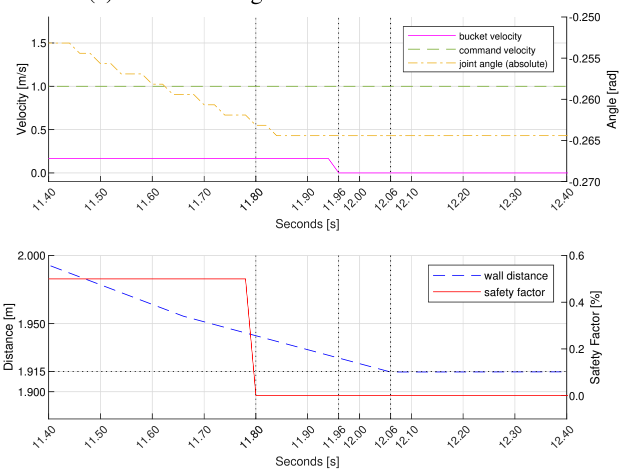
C. Network Analysis

To analyse the teleoperation performance with and without the ROS middleware over the different networks - 5G network, Wi-Fi network and cable communications, round trip latency tests were conducted. The test results for the simulation study conducted are presented in Fig. 10.

The extra latency incurred before and after introducing ROS middleware are 82%, 194%, and 6.7% for cable, Wi-Fi and

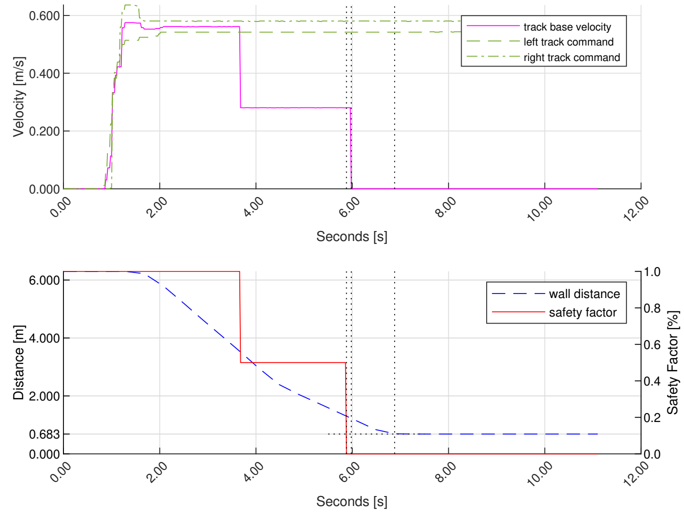


(a) Full time range of bucket collision test

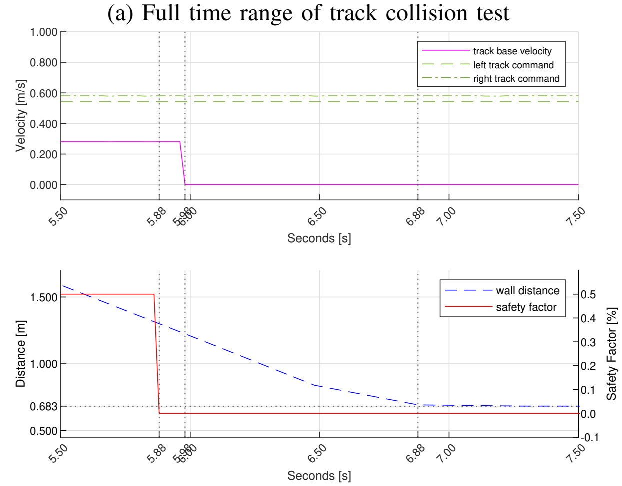


(b) 1 second time-frame when safety is triggered

Fig. 6: An example of the end-effector position and velocity with user's command velocity and safety factor over time during the arm collision test in simulation.



(a) Full time range of track collision test



(b) 2 seconds time-frame when safety is triggered

Fig. 7: An example of the track velocity with user's command velocity and safety factor over time during the drive collision test in simulation.

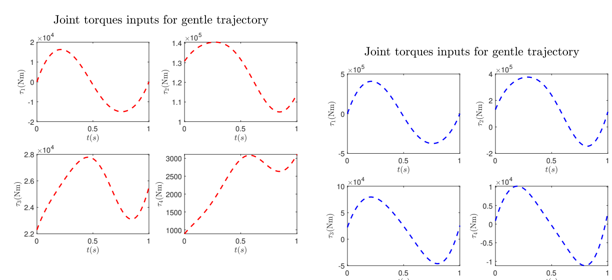


Fig. 8: Joint torques acting about the direction of the joint axis for each of the excavator's joint for both the slow (left) and the fast (right) trajectory.

5G network configurations respectively. Using a 5G network configuration with middleware demonstrated least impact to the latency comparatively.

The teleoperation latency test results for real-time experiments performed, measured at teleoperation master system, are shown in Fig. 11. It is measured from the time when non-zero joystick input (>0.1) is sent to teleoperation command centre until the time when command centre receives excavator status from excavator to reflect that joint angle change by 0.1 degree. Majority of the latency measures were recorded below 200ms. The outliers exceeding 200ms are identified to be caused by the joystick inputs that were too small to overcome the joint hydraulic inertia to trigger physical movements.

IV. Conclusion

In this paper, we have proposed and implemented a comprehensive system design and architecture for a real-time remote-controlled excavator system specifically designed for construction environments. By integrating a teleoperation command center, a wireless network infrastructure, a middleware layer, and a safety system, we have addressed key challenges in remote excavator operation, such as safety, communication,

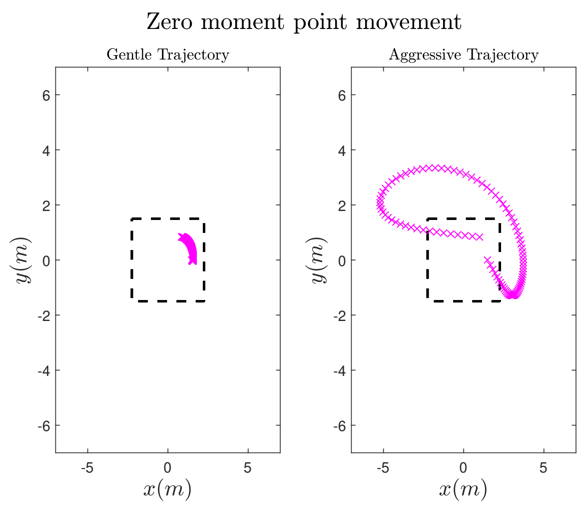


Fig. 9: Movement of the zero moment point for both the trajectories relative to the excavator's support polygon

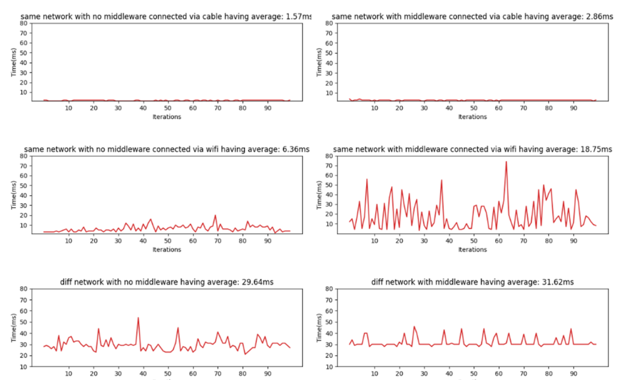


Fig. 10: Teleoperation latency test in simulation.

and system management. The system design demonstrates enhanced safety features, including collision detection and toppling risk detection while the wireless network infrastructure ensures reliable communication. The proposed architecture provides a solid foundation for further research and development in automating excavator operations, improving human-machine interaction, and conducting real-world deployments.

Future work will focus on real-world deployment and validation that is essential to assess the system's performance, practicality, and safety in various built environment scenarios. By addressing these areas, we can further enhance the capabilities and applicability of remote-controlled excavators for the construction industry.

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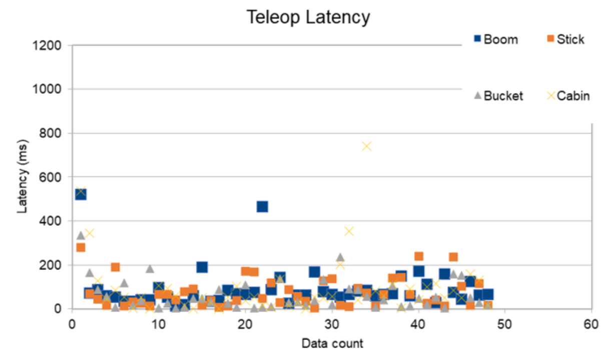

Fig. 11: Latency results in real time

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