Exploring delay and its impact on trust in teleoperated robots

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Teleoperation enables humans to remotely control robots, often in environments that are hazardous, inaccessible, or impractical for direct human presence. Trust in robotics, particularly in human-robot interaction (HRI), is a critical area of research. This study investigates how different levels of input delay affect performance-based trust in a teleoperated robot during a collaborative task. A controlled latency mechanism was implemented within the robot control pipeline to introduce systematic input delay between user actions and robot response. Participants completed a short survey and a baseline question assessing general attitudes toward robots and teleoperation. Results indicate that latency may primarily influence operational aspects of trust, such as perceived reliability, responsiveness, and controllability.

Human-Robot Interaction, Trust, Teleoperation

1. INTRODUCTION

As robots increasingly take on roles traditionally performed by humans [3], trust in these systems has become a critical area of research. While trust in robotics has been widely studied, the specific impact of delay in teleoperation and its impact on performance-based trust remains under-explored. This project addresses that gap. Trust in robotics, specifically in human-robotic interaction (HRI) [5], is influenced by multiple factors. In the context of teleoperation, one unexplored factor is latency.

Previous HCI research suggests that latency can negatively influence users' perceptions of system responsiveness, reliability, and overall interaction quality [4, 17]. In teleoperation contexts, these effects may extend to users' trust in a robot's ability to perform tasks effectively. However, it remains unclear what level of latency begins to affect trust. Prior research has shown that when a robot behaves in an unexpected manner without explanation, trust can decline rapidly [13]. This paper explores how latency may influence trust during teleoperation, building on existing research in robotics, trust, and human-robot interaction.

The concept of trust in automation and teleoperation presents a unique set of challenges [11]. Unlike human operators, robot's design alone is not enough to create the appropriate level of trust. The robot has to not only gain the trust of the user but maintain that trust for successful work to be completed [8]. In contrast, when a robot performs the same action, users may experience a sharp reduction in trust, assuming that the robot is incapable of completing the task consistently. This gives a strong indication of how fragile trust is in human-robot interaction [9].

This principle suggests that even minor unexpected robotic behaviour during teleoperation, such as those introduced by latency, may reduce user confidence. If a user issues a command and observes a delayed or inconsistent response, this may be seen as system unreliability rather than as a communication delay. Following this, trust in the robot may decrease [13]. This highlights the importance of understanding how input delay in teleoperated systems contributes to the trust dynamic.

Outside the domain of teleoperation, latency has been widely studied in relation to user experience and system usability. For example, one study used physiological sensors to measure levels of user frustration induced by system delays in a mobile gaming context [18]. That study found that, within a range of latency between 0 to 400ms, higher latency led to increased user frustration and reduced overall performance. While this study was not focused on robotics, the results show an important psychological

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response: as delays increase, users become more frustrated and less confident in system reliability.

It is reasonable to assume that similar emotional responses of frustration would also occur during teleoperation, where delays in system feedback or response could lead to comparable frustration. In a robotic context, however this frustration may also cause a reduction in trust [1]. Therefore, if latency in a teleoperated system causes noticeable performance issues, it is likely to reduce not only user satisfaction but also users' overall trust in the robotic system's reliability and ability to complete its task.

Beyond robotics, latency has long been a topic of interest within Human-Computer Interaction (HCI), where system responsiveness is recognised as a key determinant of user experience, perceived control, and task performance. Early HCI research demonstrated that delays between user actions and system responses can disrupt interaction flow, reduce the sense of direct manipulation, and negatively affect user satisfaction and performance [4]. More recent work has continued to show that latency influences users' perceptions of usability, engagement, reliability, and overall system quality across a wide range of interactive technologies, including contemporary AI-assisted systems [16, 17]. These findings suggest that responsiveness plays a central role in shaping how users evaluate interactive systems. Teleoperation represents a particularly interesting extension of this HCI problem, as latency is embodied through the physical actions of a robot rather than being confined to a screen-based interface. Consequently, delays may influence not only perceived usability and controllability, but also performance-based trust in the robot itself.

2. BACKGROUND AND RELATED WORK

2.1. Trust in HRI

Trust is a foundational aspect of Human-Robot Interaction (HRI) and is critical for the successful integration of robots into everyday and professional environments [9, 10]. Without appropriate trust, users may reject, misuse, or excessively monitor even highly capable robotic systems. Trust in HRI is commonly conceptualised as comprising both integrity-based and performance-based dimensions [9]. Integrity-based trust relates to social and interpersonal factors such as perceived intentions, personality, or anthropomorphic characteristics, whereas performance-based trust is grounded in a robot's perceived ability to complete tasks reliably, safely, and effectively [14]. For teleoperated tasks, performance-based trust is particularly relevant because user evaluations are strongly influenced by system responsiveness, accuracy, and reliability. Unlike long-term social interactions with robots, teleoperation often involves short-term, goal-oriented activities where users must rely on the robot's operational performance to achieve successful outcomes. Consequently, performance-based trust provides a practical framework for investigating how system characteristics influence user perceptions during teleoperation.

2.2. Trust in Teleoperation

Teleoperation enables humans to remotely control robotic systems in environments that are hazardous, inaccessible, or impractical for direct human involvement [3]. Applications include bomb disposal, underwater exploration, disaster response, and space operations, where successful performance depends on effective communication between the operator and the robot. A key challenge in teleoperation is the physical and informational separation between the operator and the robotic platform. Unlike co-located interaction, teleoperation relies on communication channels that may introduce latency, reduced feedback fidelity, or other disruptions [18]. Such disruptions can affect users' ability to predict robot behaviour and maintain effective control. Previous research has shown that trust can decline when robotic systems behave in unexpected ways, particularly when users are unable to understand the reasons behind the behaviour [13, 15]. In teleoperation, delays between user actions and robot responses may create similar perceptions of unpredictability or unreliability. As a result, understanding how system responsiveness shapes users' trust is essential for the design of effective teleoperated systems.

2.3. Latency and the Research Gap

Latency has been widely studied within HCI, where responsiveness is known to influence user experience, perceived control, frustration, and task performance [4, 16, 17]. Research across a variety of interactive systems has shown that delays can disrupt users' sense of direct manipulation, reduce satisfaction, and negatively affect perceptions of system quality. Similar effects have also been observed in studies examining the relationship between delay and user frustration [18]. In teleoperation contexts, latency may be particularly important because delays are embodied through the actions of a physical robot. Delayed responses can make robot behaviour appear less predictable, potentially affecting confidence in the robot's ability to perform tasks effectively. Although trust in HRI and the effects of latency have both been studied extensively, relatively little research has directly examined how varying levels of latency influence performance-based trust in teleoperated systems. This paper addresses that gap



Figure 1: *Low-Cost 3D printed arms designed by [7].*

by examining how different levels of input delay affect trust in a teleoperated robot during a constrained manipulation task. By combining subjective trust measures with qualitative participant feedback, the study aims to provide insight into the relationship between system responsiveness and performance-based trust in teleoperation.

3. SYSTEM DEVELOPMENT

The system was developed iteratively, moving from an initial prototype to a full teleoperation setup designed to study the effects of temporal delay in human–robot interaction. Early exploration used a low-cost leader–follower robot configuration [7] (*Figure 2: Top*), in which artificial delay was introduced between user commands and robot response. This stage was primarily used to establish whether latency could be reliably imposed as a controllable experimental variable in physical robot behaviour.

Initial trials revealed that manipulating delay dynamically introduced noticeable instabilities in robot behaviour, particularly when the system attempted to reconcile incoming and buffered actions. While these effects highlighted limitations of the early implementation, they also reinforced the viability of delay as a meaningful experimental manipulation in embodied interaction.

The system was then transitioned to a more capable dual-arm platform (Tiago, PAL Robotics), enabling a closer approximation of realistic teleoperation scenarios (see *Figure 2: Bottom*). This shift was motivated by the need for greater physical stability, richer interaction capability, and improved suitability for participant-facing studies.

Within this platform, delay was implemented as an intermediary stage in the control loop, ensuring that all user actions were consistently withheld before execution. This architectural decision was central to the study design, as it allowed delay to be applied uniformly across interaction modalities rather than embedded within individual behaviours. In moving to this structure, several exploratory features were removed in favour of a more stable and controllable experimental setup.



Figure 2: *Left: Dual Arm Tiago Robot by PAL Robotics. Right: Tiago moving block in between obstacles in a maze.*

Several iterations of the control interface were explored to balance realism, safety, and experimental control. Keyboard input was replaced with a game controller [12], while low-level joint control was replaced with higher-level motion planning through MoveIt! [2]. These changes improved predictability and reduced cognitive load. The final task required participants to grasp a block and navigate it through a constrained maze without collision under varying delay conditions (see *Figure 2: Right*).

Further refinements focused on ensuring that interaction remained stable under delay. Continuous input was found to produce unpredictable command accumulation, particularly at higher latencies, and was replaced with discrete input steps to improve controllability. Additional constraints were introduced to ensure consistent starting conditions and to maintain safe, repeatable movement boundaries.

Overall, the development process progressively shifted the system from a technically expressive but unstable prototype towards a constrained and experimentally focused platform. Each iteration reflected a trade-off between realism, controllability, and experimental validity, resulting in a setup designed specifically to isolate the perceptual and behavioural effects of delay in teleoperated interaction.

4. EXPERIMENTAL METHOD

4.1. Overview

This study used a within-subjects design to examine how varying levels of input delay influence trust in teleoperated robot systems. Participants completed a constrained manipulation task using a Tiago dual-arm robot, in which they controlled a single arm to move a cube made from a stack of LEGO bricks through a physical maze. The task was designed to require continuous corrective action under time pressure, making it sensitive to variations in system responsiveness. Trust was assessed at multiple points using a standard subjective questionnaire [6].

4.2. Participants and Recruitment

Twelve participants were recruited through university internal mailing lists and in-person invitations. All participants were 18 years or older and reported no impairments affecting motor control. Prior to participation, individuals received an information sheet outlining the study and provided written informed consent. Ethical approval was granted by the university ethics committee (approval code redacted for anonymity).

4.3. Apparatus and Setup

The study was conducted in an HRI laboratory using a Tiago dual-arm robotic platform (*Figure 2*). For safety and experimental control, one arm was fixed in place, and participants interacted using the remaining arm only.

Participants controlled the robot from a suitable distance within the same room via a Logitech F710 wireless gamepad. Input was intentionally constrained to discrete directional commands using the D-pad and button-based actions, reducing continuous control variability and ensuring consistent interaction under delayed conditions.

A controlled latency mechanism was implemented within the robot control pipeline to introduce systematic input delay between user actions and robot response. This ensured that all movement commands were consistently deferred before execution, enabling precise manipulation of delay as an experimental variable. The delay was applied specifically to arm movement commands, while maintaining consistent handling of other system functions.

4.4. Procedure

Participants were individually welcomed to the HRI Lab and given an information sheet explaining the study's aims, procedures, and their rights. After reviewing the information and signing the consent form, participants completed a short demographic survey and a baseline question assessing general attitudes toward robots and teleoperation.

Participants were then introduced to the Tiago robot and trained on the control system using the gamepad. They were allowed to practise controlling the robot under zero-delay conditions until they reported feeling confident in their ability to manipulate the robotic arm. Once ready, they completed a second baseline trust survey specific to the robot's performance.

The primary experimental task involved using the robot to pick up a cube and move it through a physical maze to an exit point without touching the maze's boundaries. This setup and these instructions were chosen to simulate real-world teleoperation scenarios where 'not touching' boundaries is important. However, the time of completion was not recorded, as the artificially induced delays, which is the main purpose of this experiment, would have skewed the results. Participants were led to believe they were somewhat penalised when touching a boundary. This was revealed to participants during the debriefing session. Each participant completed ten trials, with each trial representing a specific pairing of input delay and maze configuration. Input delays were set at five levels: 0 ms, 150 ms, 300 ms, 450 ms, 600 ms.

Participants completed the task using two maze configurations: Maze A: A layout with a single, large central obstacle, Maze B: A layout with two smaller offset obstacles (see *Figure 3*).

To mitigate order effects, the sequence of delay-maze combinations followed a rotating Latin square design. That is, each participant received the same ten pairings, but in a systematically rotated order. This rotation ensured that each delay and maze pairing appeared in every ordinal position across participants, counterbalancing learning and fatigue effects.

After each trial, participants completed the 'Checklist for Trust between People and Automation' [6], a widely used survey instrument designed to measure a person's trust in automated systems. This standardised questionnaire was used to assess participants' trust in the robot's performance under that specific delay condition. Both Likert-scale responses from the checklist, and open-ended responses were collected to allow for quantitative and qualitative analysis.

At the end of the study, participants were debriefed and informed of the experiment's true aim—to explore the effect of artificial input delay on trust formation and degradation during teleoperated tasks. The purpose of delay manipulation and its relevance to real-world teleoperation scenarios (e.g. network-induced lag) was explained. Participants were then thanked for their contribution and given an opportunity to ask any final questions.

4.5. Qualitative Analysis

Open-ended responses collected following each trial were analysed using an exploratory thematic approach. Responses were reviewed by the researchers and grouped into recurring themes relating to responsiveness, predictability, controllability, and adaptation to delay. Given the relatively small dataset, the qualitative analysis was intended to

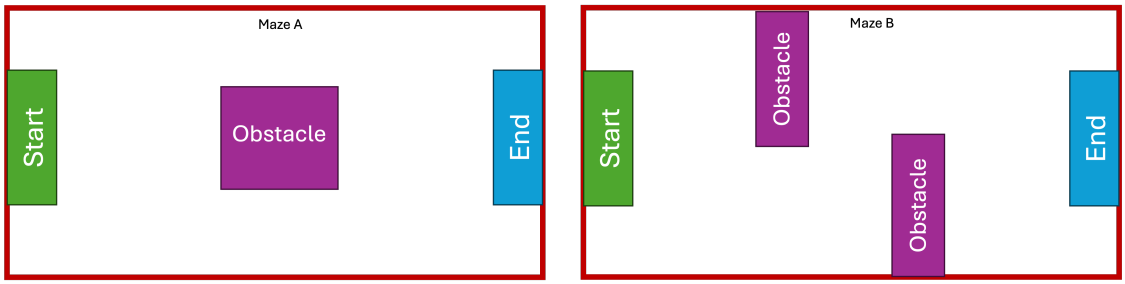

Figure 3: *Maze configurations as used during the cooperative teleoperation task (Left: Maze A; Right: Maze B).*

Delay	Mean Trust (Maze A)	Mean Trust (Maze B)
0 ms	5.70	5.74
150 ms	5.24	5.59
300 ms	5.40	5.24
450 ms	5.24	5.48
600 ms	5.06	5.12

Table 1: *Average trust scores for each condition.*

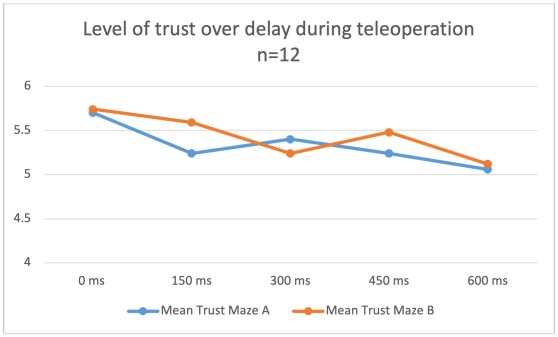

Figure 4: *Average level of trust for each delay condition in our two maze setup. Note the Y-Axis scale as it may indicate a more dramatic decrease of delay than what the actual data shows.*

identify common participant experiences and provide context for the quantitative findings rather than develop a formal qualitative theory.

5. RESULTS

This experiment used two maze layouts and 5 levels of delay between input by the teleoperator and action by the robot. The five levels of delay were: 0, 150, 300, 450, 600 ms.

Descriptively, trust scores were highest under the 0 ms condition and generally declined as latency increased. Even though this was not entirely unexpected, the decline appears to be modest rather than dramatic and the alternative layout of Maze B, as it required finer navigation adjustments to avoid the obstacles, may buffer the trust drop in some conditions. Importantly, the effect of an increasing delay looks gradual, and not catastrophic, with increasing input latency showing a small downward trend in trust ratings, although the effect was not statistically significant in this sample (*Table 1* and *Figure 4*).

Participants completed the Jian Trust in Automation scale [6] following each trial. Negatively worded items were reverse scored prior to analysis such that higher values consistently reflected greater trust. Mean trust scores were then calculated for each participant under each delay and maze condition. The scale demonstrated excellent internal consistency across conditions ($\alpha = .93$).

A two-way repeated-measures ANOVA was conducted with Delay (0 ms, 150 ms, 300 ms, 450 ms, and 600 ms) and Maze Configuration (A and B) as within-subject factors. Descriptively, trust scores were highest under the 0 ms condition and generally declined with increasing latency (Table 1; Figure 4). However, there was no statistically significant main effect of Delay, $F(4,44)=1.57$, $p=.199$. Likewise, no significant main effect of Maze Configuration was observed, $F(1,11)=1.04$, $p=.329$, and there was no significant Delay $\times$ Maze interaction, $F(4,44)=0.46$, $p=.765$. Consequently, while the observed trend is consistent with the expectation that increasing delay might reduce trust, the present study does not provide sufficient evidence to conclude that latency had a statistically reliable effect on trust ratings.

Across both maze configurations, trust scores remained relatively stable between 0 ms and 450 ms delay, before decreasing descriptively at 600 ms. Although this pattern did not reach statistical significance, it may suggest that participants were able to tolerate moderate levels of latency during the task without substantial reductions in perceived trust.

Exploratory inspection of individual questionnaire items suggested that responses relating to reliability, confidence, and dependability varied more across delay conditions than responses relating to deception, harmful intent, or integrity. Given the exploratory nature of this examination, no formal statistical conclusions are drawn from these observations.

5.1. Qualitative Findings

Participants frequently described higher latency conditions as ”sluggish”, ”harder to control”, and ”less predictable”. A recurring theme was uncertainty regarding whether commands had been successfully registered and when they would be executed. Several participants reported that delayed execution reduced their confidence in the robot's responsiveness despite continuing to trust that commands would eventually be carried out. A second theme concerned adaptation. Participants reported modifying their interaction strategies by slowing the rate of input, spacing commands further apart, and attempting to anticipate future robot movements. However, these adaptations did not fully eliminate difficulties associated with delay. Participants continued to report overshooting, command accumulation, and uncertainty regarding the robot's future actions, particularly under the higher latency conditions.

6. DISCUSSION AND CONCLUSION

This study investigated the impact of input latency on trust in a teleoperated robot during cooperative tasks. Although statistical significance was not observed, the results revealed a descriptive downward trend in trust scores as latency increased, particularly at the highest delay condition (600 ms). However, we must also keep in mind the small sample size of this study, and, due to the recruitment happening within a university setting, this sample was also biased towards a more tech-savvy population.

The findings suggest that latency may primarily influence operational aspects of trust, such as perceived reliability, responsiveness, and controllability, rather than social or moral perceptions of the robot. Participants did not appear to interpret delayed behaviour as deceptive or malicious; instead, qualitative responses suggest that increased delay reduced confidence in the robot's responsiveness and predictability.

An important observation is that trust remained comparatively stable across moderate delay levels. This may suggest that users are capable of adapting to moderate latency during short-term interaction tasks, particularly when the delay remains predictable. Such findings are relevant for teleoperation and remote robotics contexts where communication latency may be unavoidable.

6.1. Implications for HCI

The observed trends align with broader HCI findings on system responsiveness and perceived control. Prior HCI research has shown that increasing latency can negatively affect user experience, reduce feelings of direct manipulation, and increase frustration. Participants in our study used similar language when describing delayed conditions, frequently characterising the robot as ”sluggish”, ”harder to control”, and ”less predictable”. This suggests that some aspects of performance-based trust in teleoperation may emerge from the same underlying mechanisms that influence user experience in other interactive systems, particularly perceptions of responsiveness and controllability. However, unlike traditional screen-based interfaces, teleoperation introduces a physical embodiment of latency. Delays are expressed through robot movements rather than visual interface updates alone. This may explain why participants tended to attribute performance issues to the robot's operational capability rather than to purely technical system limitations. Understanding how responsiveness influences trust in physically embodied systems therefore represents an important extension of existing HCI latency research.

6.2. Limitations and Future Work

The study is limited by its relatively small sample size (n=12), which may have reduced statistical power to detect smaller effects. Future work should explore larger participant samples and longer interaction periods to better understand how latency influences trust calibration over time. Further analysis of qualitative responses may also help identify specific behavioural factors contributing to perceived reliability under delayed control conditions.

A further limitation is the absence of objective behavioural measures. Metrics such as collision frequency, corrective inputs, command rates, or task completion times may have provided additional insight into how latency influences both performance and trust. Future studies should combine subjective trust measures with behavioural indicators to better understand the relationship between observed performance and trust formation.

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