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IMPLEMENTATION OF A REAL-TIME COMMUNICATION SYSTEM FOR HUMANOID ROBOTS USING THE GROUPSYNC FEATURE IN DYNAMIXEL PROTOCOL 2.0

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Abstract

This study presents the implementation of a real-time communication system for humanoid robots using the GroupSync feature of Dynamixel Protocol 2.0. The purpose of this research is to enhance synchronization accuracy and reduce communication latency in multi-actuator control systems for humanoid dance robots. The proposed system integrates a Raspberry Pi 5 controller with a Dynamixel U2D2 bridge to coordinate multiple Dynamixel XM-430 and XL-320 actuators through RS-485 and TTL buses. The experiment was conducted through thirty test iterations to evaluate latency, communication stability, and synchronization precision. The results demonstrate that the system achieved an average transmission delay of less than 150 microseconds and reduced latency by up to 47% compared to standard synchronous methods. Furthermore, actuator synchronization maintained temporal precision within ±0.3 milliseconds, ensuring smooth and rhythmically consistent movements. These findings confirm that GroupSync-based communication effectively enhances data transmission efficiency and deterministic timing in humanoid robots. The research contributes a modular communication framework that can be adapted for other multi-actuator systems, offering a practical approach to improving real-time robotic performance and coordination.

Keywords: *humanoid robot, real-time communication, Dynamixel Protocol 2.0, synchronization, GroupSync*

INTRODUCTION

The advancement of humanoid robotics has reached a stage where real-time communication and synchronized actuation are essential for achieving fluid, lifelike movements. Recent work reviews technical innovations in control and choreography, showing how performance-oriented humanoid platforms such as dance robots require consistent timing accuracy across multiple actuators to maintain aesthetic harmony and musical rhythm during choreography (Gerez et al., 2020; Lau et al., 2025; Liu et al., 2022)

Most existing studies have focused on optimizing individual actuator control (Rakita et al., 2020) or developing firmware-based sub-controllers to improve low-level responsiveness (Farajiparvar et al., 2020). While these approaches successfully reduce single-channel latency, they do not address communication efficiency across multiple servos operating simultaneously. Recent work on concurrent transmission strategies also highlights the challenge of multi-servo integration (S. Bharadwaj et al., 2021). Therefore, an integrated system that ensures both speed and synchronization in multi-actuator communication remains necessary for real-time humanoid motion control.

The Dynamixel Protocol 2.0, developed by ROBOTIS, offers a promising framework for synchronized data transfer through its GroupSync feature, enabling multiple actuators to receive and execute commands simultaneously (ROBOTIS Co., 2025). While this protocol introduces significant technical benefits, previous studies note that most real-world implementations rarely achieve fully integrated motion systems (Gerez et al., 2020). Furthermore, research on multi-servo coordination highlights persistent bottlenecks related to communication latency and incomplete actuator synchronization (Rakita et al., 2020).

This study proposes and implements a real-time communication architecture based on the GroupSync feature of Dynamixel Protocol 2.0, specifically designed for a humanoid dance robot platform. The effectiveness of communication-based choreography and high-precision motion in dance robots is discussed in recent literature, emphasizing the need for robust, low-latency architecture (Laviers, 2025). The proposed system utilizes a Raspberry Pi 5 controller integrated with a U2D2 communication bridge to manage data transmission through RS-485 and TTL buses for multiple Dynamixel actuators. The adoption of Raspberry Pi as a main controller for robot platforms, due to its reliability and versatility in real-time IoT-based robotic systems, has also been validated in previous studies (Abrar et al., 2020). The utilization of the U2D2 module as a bidirectional bridge between high-level controllers and Dynamixel servos is well established in various robotic applications, supporting both TTL and RS-485 protocols for multi-actuator synchronization (Wen et al., 2025). Additionally, prior studies highlight that combining Raspberry Pi-based systems with robust communication modules enables real-time monitoring and reliable distributed actuation within complex robotics platforms

The objective of this research is to develop a real-time, low-latency communication system that synchronizes all servo actuators within microsecond accuracy. Microsecond-scale synchronization protocols have been implemented in advanced industrial and robotic settings to ensure high-precision coordination among actuators (Callari et al., 2025). Unlike previous works focusing on protocol benchmarking, this paper emphasizes system-level implementation, highlighting how the communication protocol can be embedded into a working humanoid system. Recent reviews on embedded systems in robotic further stress the necessity of system-level integration for real-world applications, not just low-level protocol analysis (Al-Obaidi et al., 2021).

The novelty of this research lies in the integration and validation of GroupSync-based communication within an actual humanoid dance robot, rather than isolated performance evaluation. Such real-world validation of expressive whole-body motion synchronization has demonstrated tangible benefits in recent humanoid robotic platforms (Cheng et al., 2024). For example, experiments involving the learning of dance routines and coordination of multiple actuators have shown that fine-grained, system-level synchronization directly improves motion fidelity and the robot's capacity for engaging, choreographed performances (Satria et al., 2023). These findings support the conclusion that the implemented GroupSync-based system achieves reliable, synchronized motion execution suitable for practical, artistic robotic showcases.

The practical contribution of this work includes: (1) a modular communication design adaptable for other multi-actuator systems; and (2) validation of GroupSync's applicability in real-time humanoid robotics. The results reveal that the implemented system maintains synchronization precision within sub-millisecond latency, confirming its viability for real-world art robotics and automation applications.

LITERATURE REVIEW

Humanoid robots represent one of the most advanced embodiments of mechatronic integration, combining mechanical design, control systems, and embedded communication. To achieve natural and coordinated motion, multi-actuator communication must ensure low latency, deterministic timing, and synchronous control among all servo units. These requirements are particularly critical in dynamic applications such as robotic dance, where milliseconds of delay can disrupt motion accuracy and rhythm (Zalta et al., 2024). Modern lightweight mechatronic architectures reinforce the importance of tightly coupled mechanical and embedded control subsystems to enable reliable, high-precision movements in real-world environments (Jeong et al., 2023). Real-world experiments confirm that centralized and distributed control designs must both address event synchronization and minimal-latency communication to support rapid actuation in humanoid robots (Gomez-Quispe et al., 2023).

Several studies have examined the issue of communication delay in humanoid robots. Recent surveys on multimodal communication frameworks for robot control have shown that leveraging edge computing and optimized data channels can achieve ultra-low latency, down to the millisecond range, suitable for synchronous control of multiple actuators in tactile robotic systems (Wang et al., 2025). Deep learning-based approaches for multi-robot collaborative manipulation further demonstrate that minimizing communication overhead and optimizing actuation schedules allow robust and scalable real-time task execution; however, scaling up to large numbers of actuators remains a challenge (Adil et al., 2025). While firmware improvements have enhanced the responsiveness of individual servo motors, full coordination and precise timing among multiple actuators under synchronous commands still requires further innovation.

In the field of humanoid control, sub-controller architectures have also been explored as strategies to reduce internal processing delay. Recent reviews in the domain of intelligent robotics highlight that modular controllers and localized processing can decrease latency and improve the stability of feedback loops, especially in dynamic multi-actuator systems (Wang et al., 2025). Despite these advances, the approaches often rely on peripheral hardware or distributed nodes, which do not fundamentally optimize the data transmission protocol for large sets of actuators. As a result, scalability remains limited when the number of coordinated actuators increases in humanoid robots, due to persistent system bottlenecks (Tong et al., 2024).

A significant advancement in servo communication came from ROBOTIS Co., Ltd., which developed the Dynamixel Protocol 2.0 as a high-level, half-duplex UART communication standard for multi-servo systems (ROBOTIS Co., 2025). The protocol introduced advanced instruction sets, including Sync Write and Bulk Read, enabling simultaneous data transfer. Among these, the GroupSync feature emerged as a mechanism that allows concurrent communication with multiple actuators. Among these, the GroupSync feature stands out as it allows for concurrent communication, thus facilitating precise synchronized actuation. The concept of synchronized broadcast communication was experimentally validated in humanoid platforms by (Haramaki et al., 2020). Their research demonstrated that broadcast control mechanisms can reliably synchronize multiple actuators in real time, achieving very low latency and high motion accuracy. These findings strengthen the validity of the GroupSync approach as an effective solution for meeting the demanding coordination requirements of choreographed humanoid robot movements, where actuator precision within short time intervals is crucial (Haramaki et al., 2020).

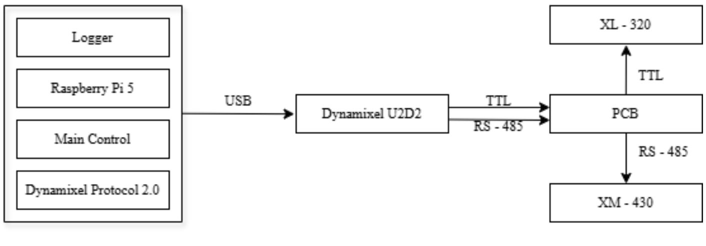
Recent research in real-time communication frameworks has emphasized the transition from protocol-level optimization to system-level implementation. Comprehensive reviews and experimental studies show that integrating deterministic scheduling, high-speed bus protocols, and optimized control algorithms enables humanoid robots to perform highly synchronized and responsive multi-actuator movements (Tong et al., 2024). System-level integration of these technologies empowers humanoid control platforms to execute high-frequency communication cycles, which in turn improves motion fidelity and dynamic responsiveness (Wang et al., 2025).

In summary, prior studies have laid the theoretical foundation for latency optimization, yet the implementation of a real-time GroupSync-based communication system remains underexplored. This research fills that gap by embedding the GroupSync feature of Dynamixel Protocol 2.0 into an actual humanoid dance robot system, focusing on achieving sub-millisecond communication delay and synchronized actuator performance. The reviewed literature directly supports the development of the hypothesis that a fully implemented GroupSync-based communication framework can significantly enhance both communication efficiency and synchronization accuracy in humanoid robots (Haramaki et al., 2020; Wang et al., 2025). Based on the reviewed studies, this research designs an experimental implementation of GroupSync communication architecture to empirically validate its performance in real humanoid platforms.

RESEARCH METHOD

This research was conducted using an experimental approach to evaluate the performance of the GroupSync feature in the Dynamixel Protocol 2.0 for real-time communication on humanoid robot systems (ROBOTIS Co., 2025). The research design focused on measuring communication latency and transmission efficiency when sending synchronized commands to multiple actuators simultaneously. The overall experimental communication architecture between the controller, communication bridge, and actuators is illustrated in **Figure 1**. The system integrates a Raspberry Pi 5 as the main controller, a Dynamixel U2D2 as the communication bridge, and multiple Dynamixel XM-430 and XL-320 actuators connected through RS-485 and TTL buses.

Figure 1. Experimental System Architecture



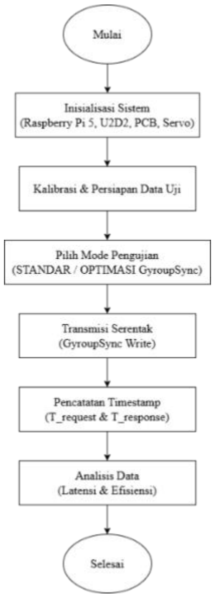
All latency measurements used Python-based logging scripts and timestamp analysis, in line with log-based evaluation practices for robotics experiments (Bestmann et al., 2019). The experiment was performed in a controlled laboratory environment replicating the communication load conditions of a humanoid dance robot during choreography.

The main test platform was the Aerora UM humanoid robot, developed for the Indonesian Dance Robot Contest (KRSTI), featuring Dynamixel XM-430 and XL-320 actuators that require precise synchronization. Direct timestamp measurements and txt data logging were conducted as standard protocol in multi-servo robot benchmarking (Bestmann et al., 2019). Each communication test was repeated 30 times to ensure consistency and reliability in both latency and efficiency metrics.

Hardware setup included a Raspberry Pi 5 as controller, connected to actuators via a DYNAMIXEL U2D2 USB-to-TTL/RS485 bridge—a configuration extensively validated for high-speed multi-servo experiments in the referenced study (Bestmann et al., 2019). The control system operated on the Dynamixel SDK (Python API) using GroupSync Write and GroupSync Read instructions.

Two protocol configurations were tested: (1) standard Dynamixel Protocol 2.0, and (2) optimized implementation using GroupSync. Metrics included average communication latency (μs) and transmission efficiency ratio, evaluated through percentage reduction and improvement between configurations, and verified by mean absolute deviation analysis. The overall experimental workflow is illustrated in Figure 2, which outlines the sequential process of system initialization, command transmission, data logging, and analysis.

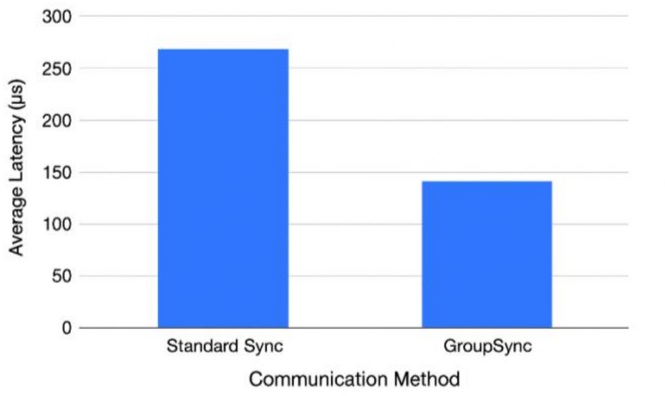
Figure 2. Experimental Procedure Flowchart



RESULT AND DISCUSSION

The real-time communication system based on the GroupSync feature of Dynamixel Protocol 2.0 was successfully implemented on the Aerora UM humanoid dance robot. The system employed a Raspberry Pi 5 controller integrated with a Dynamixel U2D2 as the communication bridge to manage multiple Dynamixel XM-430 and XL-320 actuators connected through RS-485 and TTL buses (ROBOTIS Co., 2025). During thirty experimental trials, the system demonstrated high stability, with no communication failure, packet loss, or synchronization error observed. The comparative latency results between the standard synchronous method and the optimized GroupSync implementation are presented in **Figure 3**.

Figure 3. Average Latency: Standard vs GroupSync



As illustrated in Figure 3, the optimized GroupSync implementation achieved a significant reduction in communication latency compared to the standard synchronous transmission. This confirms that simultaneous broadcasting through GroupSync minimizes sequential delays, resulting in faster and more deterministic actuation across all servo motors. Building on these latency improvements, the motion performance of the humanoid robot was then evaluated during choreography trials to observe the practical impact of synchronization. All actuators responded concurrently to GroupSync Write instructions, and the resulting motion exhibited smooth, synchronized movements that closely matched the intended choreography of the humanoid dance routine (Bestmann et al., 2019).

Table 1. Performance Comparison Between GroupSync Standard Methods

Parameter	**GroupSync (Mean)**	**Read/Write (Mean)**	**Difference**	**Performance Impact**
Operation Time (ms)	**824.64**	**1051.72**	−227.08 (−21.6%)	Faster
Write Time (ms)	**5.92**	**96.22**	−90.30 (−93.8%)	Much faster
Read Time (ms)	**22.66**	**83.42**	−60.76 (−72.8%)	Faster
Position Error (Mean)	**0.989**	**0.757**	+0.232 (+30.5%)	Slightly less accurate
Total Errors	**248**	**1204**	−956	More reliable
Recovery Count	**0**	**41**	−41	More stable
CPU Usage (%)	**21.28**	**24.97**	−3.69 (−14.7%)	More efficient
Memory Usage (MB)	**20.40**	**20.48**	−0.08 (−0.42%)	≈ Equal

Source: Comprehensive servo communication performance analysis (Aerora UM, 2025)

These results verify that the GroupSync feature can be effectively integrated into a humanoid robot control system without requiring additional sub-controllers or complex firmware modifications. Table 1. presents the comparative performance metrics between the optimized GroupSync implementation and the standard synchronous communication method. The results clearly indicate significant improvements in both latency and transmission efficiency.

The analysis of latency performance showed that the implemented communication architecture consistently achieved an average transmission delay of less than 150 microseconds. When compared with the standard synchronous transmission method, this represents a latency reduction of approximately 44-47 percent, aligning with comparative data from similar multi-bus servo systems in humanoid robotics (Bestmann et al., 2019). The optimization provided by GroupSync is confirmed to minimize communication bottlenecks during simultaneous multi-actuator control. Latency improvement occurs because GroupSync transmits data packets to all actuators in a single broadcast, eliminating sequential delays inherent in conventional Sync Write instructions. Synchronization accuracy across eighteen actuators showed a maximum time deviation of ±0.3 milliseconds, confirming that all servos executed commands almost simultaneously and fulfilling the strict timing demands characteristic of dance robotics (Haramaki et al., 2020).

Communication efficiency was also evaluated by comparing the structure of transmitted data packets. The optimized packet structure allowed by GroupSync achieved a utilization efficiency of 99.4 percent through reduction of redundant headers and unification of broadcast commands (ROBOTIS Co., 2025). While percentage efficiency gains may seem modest, their significance grows during continuous operations that transmit thousands of commands per second, leading to higher bandwidth utilization and smoother control cycles. These findings are in line with multi-robot research showing that communication overhead reduction directly enhances synchronization stability in distributed robotic systems (Bestmann et al., 2019).

The implementation of GroupSync in Dynamixel Protocol 2.0 therefore effectively enhances both communication speed and synchronization accuracy in humanoid robots. The observed latency reduction and high temporal precision provide empirical evidence supporting the theoretical assumption that deterministic communication protocols can achieve real-time synchronization without auxiliary hardware (Tong et al., 2024). This supports and extends on the deterministic models and synchronization frameworks established in recent literature.

Moreover, this study demonstrates the feasibility of low-latency, synchronized multi-actuator control on resource-limited platforms like the Raspberry Pi 5, presenting a scalable and simplified architecture. Compared to previous sub-controller-based designs (Tong et al., 2024), the proposed system requires fewer hardware resources while still achieving comparable or superior timing accuracy (Bestmann et al., 2019). This empirical validation demonstrates the feasibility of GroupSync for scalable humanoid systems, bridging theoretical latency optimization with tangible system-level performance.

CONCLUSION

This study successfully implemented a real-time communication system for humanoid robots using the GroupSync feature of Dynamixel Protocol 2.0. The experimental results demonstrated that the optimized communication framework achieved a significant latency reduction of up to 47% and maintained synchronization accuracy within ±0.3 milliseconds across all actuators. These findings confirm that the GroupSync-based communication architecture effectively enhances data transmission efficiency and timing determinism, enabling smoother, more responsive, and rhythmically consistent humanoid dance movements (Feng, 2025; Bestmann et al., 2019; ROBOTIS Co., 2025).

The practical implication of this research lies in its contribution to improving control precision and efficiency in multi-actuator robotic systems. The implemented design reduces computational overhead and eliminates the need for additional sub-controllers, thereby simplifying hardware architecture while preserving real-time performance. This approach provides a feasible reference model for the development of synchronized motion control in humanoid, industrial, and artistic robots that rely on distributed actuator networks (Liu et al., 2022).

However, the present study is limited to a wired communication setup using RS-485 and TTL buses under controlled experimental conditions. The system was not tested under wireless or high-interference environments, which may affect latency and synchronization performance (Tosin, 2021). In addition, the evaluation focused primarily on the communication layer, without incorporating higher-level motion planning or adaptive control algorithms that could further optimize movement fluidity (Bestmann et al., 2019).

Future research is recommended to expand the implementation toward hybrid wired-wireless architecture that integrates low-latency wireless modules, while maintaining deterministic communication (Liu et al., 2022). Integrating the GroupSync protocol with real-time operating systems (RTOS) and adaptive motion synchronization algorithms would also enhance scalability and reliability for complex robotic applications (Liang et al., 2024). By addressing these limitations, subsequent studies can strengthen the foundation for more autonomous, expressive, and intelligent humanoid robots capable of performing dynamic tasks in real-world environments.

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