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Tino V2, the revenge of the maze (Temporal Title)

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Dedicated to my family.

Abstract

Here goes the abstract.

Keywords: key, words, go, here

Abstract in lingua italiana

Qui va inserito l'abstract in italiano.

Parole chiave: qui, vanno, le, parole, chiave

Contents

1 | Introduction and Project Overview

1.1. Background and Context

This section will provide a comprehensive overview of the social robotics field and human-robot interaction research, establishing the foundation for understanding the Tino robot project's significance. The discussion will begin with a brief history of social robotics development and its evolution in academic and commercial applications. Following this, the section will introduce the Tino robot project as developed at Politecnico di Milano, detailing its role in advancing human-robot interaction research within the academic community. An overview of the original Tino robot will be presented, including its design philosophy, intended applications, and practical use cases in social interaction scenarios. Finally, the research context will be established within the AIRLab robotics laboratory, highlighting the interdisciplinary approach and research objectives that drive the Tino project development.

1.2. Legacy Tino System Overview

This section will present a detailed technical analysis of the original Tino robot architecture, providing the foundation for understanding the improvements made in Tino V2. The discussion will begin with a comprehensive description of the legacy system's hardware and software components, focusing on the Raspberry Pi-based control system and its inherent limitations in processing power and real-time performance. The original omnidirectional movement system utilizing the Triksta base will be examined, including its mechanical design, control algorithms, and operational characteristics. The basic sensor setup and capabilities of the legacy system will be detailed, covering the available sensing modalities and their integration into the robot's behavior system. Previous applications and use cases will be documented, demonstrating the robot's practical deployment in social interaction scenarios. Finally, the section will identify specific limitations and areas for improvement that motivated the development of Tino V2, including hardware constraints, software architecture issues, and performance bottlenecks.

1.3. Project Motivation and Objectives

This section will articulate the driving forces behind the Tino V2 development project and establish clear objectives for the research and development effort. The discussion will begin by identifying key limitations of the legacy system that necessitated a comprehensive redesign, including inadequate computational resources, limited sensor capabilities, and reliability issues. The need for improved localization and navigation capabilities will be established, highlighting the requirements for precise positioning in complex indoor environments and robust SLAM implementation. Requirements for VR integration and immersive interaction will be detailed, explaining how these capabilities extend the robot's potential applications and research value. Hardware reliability and performance enhancement needs will be discussed, focusing on the mechanical improvements required for sustained operation and user interaction. The section will conclude with an overview of research goals for advanced human-robot interaction, establishing the academic and practical contributions expected from the Tino V2 project.

1.3.1. Technical Objectives

This subsection will detail the specific technical goals that guide the Tino V2 development process. The migration from the Raspberry Pi platform to the NVIDIA Orin Nano will be explained, including the performance benefits and expanded capabilities this transition enables. The implementation of robust SLAM (Simultaneous Localization and Mapping) and sensor fusion techniques will be outlined, describing how these technologies address the localization challenges identified in the legacy system. The development of real-time human detection and pose estimation capabilities will be presented, explaining the integration of computer vision and machine learning technologies for enhanced human-robot interaction. The creation of VR-compatible control and interaction systems will be detailed, describing the software architecture and communication protocols required for seamless virtual reality integration. Finally, the improvement of mechanical reliability and performance will be discussed, covering hardware redesign efforts and component upgrades that enhance the robot's operational capabilities.

1.3.2. Research Objectives

This subsection will outline the research contributions and academic goals of the Tino V2 project. The investigation of hybrid localization approaches combining SLAM with Ultra-Wideband (UWB) positioning will be presented as a novel contribution to mobile robotics research. The development of atomic movement systems specifically designed for VR control will be detailed, explaining how this approach enables more natural and intuitive human-robot interaction paradigms. The exploration of advanced human-robot interaction paradigms will be discussed, focusing on how the enhanced sensing and control capabilities enable new forms of social interaction and user engagement. The study of real-time pose detection integration with robot behavior will be presented, demonstrating how human posture and gesture recognition can be incorporated into responsive robot behaviors for more natural interaction experiences.

1.4. System Requirements and Constraints

This section will establish the technical specifications and operational constraints that define the Tino V2 system design. Performance requirements for real-time operation will be detailed, including computational load specifications, response time requirements, and throughput expectations for various system components. Accuracy requirements for localization and human tracking will be specified, establishing the precision standards necessary for effective navigation and interaction capabilities. VR integration constraints and specifications will be outlined, including latency requirements, data exchange protocols, and synchronization standards required for seamless virtual reality operation. Physical constraints will be discussed, covering weight limitations, size restrictions, and power consumption requirements that influence the hardware design and component selection. Finally, reliability and robustness requirements for social interaction will be established, defining the operational standards necessary for safe and effective human-robot interaction in various environments.

1.5. Thesis Structure and Contributions

This section will provide readers with a clear roadmap of the thesis organization and highlight the key contributions of the research. An overview of the thesis organization and chapter flow will be presented, explaining how each chapter builds upon previous work and contributes to the overall narrative of the Tino V2 development project. The summary of main technical contributions will detail the engineering innovations and system improvements achieved in the project, including hardware upgrades, software architecture enhancements, and integration achievements. The summary of research contributions will highlight the academic value of the work, including novel approaches to mobile robot localization, human-robot interaction paradigms, and VR integration techniques. Key innovations and novel approaches introduced in the project will be emphasized, demonstrating how the work advances the state of the art in social robotics and mobile robot systems. Finally, the expected impact and applications of the developed system will be discussed, explaining how the Tino V2 platform enables new research opportunities and practical applications in human-robot interaction, education, and social robotics research.

2 | Technology Research and Selection

2.1. Localization Technologies Review

This section will provide a comprehensive analysis of available localization technologies for mobile robotics applications, establishing the foundation for the technology selection decisions made in the Tino V2 project. The review will begin with an examination of Visual Odometry (VO) approaches, including both monocular and stereo camera implementations, analyzing their strengths in feature-rich environments and limitations in scenarios with poor lighting or repetitive textures. The discussion will cover ORB-SLAM3 capabilities for RGB-D sensor integration, SVO (Semi-direct Visual Odometry) advantages for fisheye and wide field-of-view cameras, and the computational requirements associated with each approach. Ultra-Wideband (UWB) positioning technology will be evaluated for its centimeter-level accuracy potential, low power consumption characteristics, and infrastructure requirements including anchor placement and calibration procedures. The analysis will address fabric penetration capabilities crucial for Tino's soft structure, Non-Line-of-Sight (NLOS) mitigation strategies, and orientation estimation challenges inherent in UWB systems. Finally, IMU and wheel encoder fusion approaches will be examined, including Extended Kalman Filter (EKF) implementations, drift accumulation issues, and performance limitations on uneven surfaces and with impulse-based movement patterns.

2.2. Human Detection Technologies Comparison

This section will systematically evaluate available human detection and tracking technologies suitable for social robotics applications. RGB-D camera solutions will be analyzed first, examining Intel RealSense and similar depth-sensing cameras for their simultaneous color and depth data capabilities, skeleton tracking potential using OpenPose and MediaPipe frameworks, and integration challenges related to physical mounting and visibility constraints within Tino's fabric structure. Thermal imaging technology will be evaluated for its potential fabric penetration capabilities, performance in low-light conditions, and limitations in providing contextual information beyond heat signatures. The discussion will cover fusion strategies between thermal sensors and other sensing modalities to achieve comprehensive human detection capabilities. LiDAR technology will be assessed for its high-resolution 3D mapping capabilities, though acknowledging its impracticality for Tino's soft structure due to vibration sensitivity and cost considerations. Machine Learning-enhanced 2D camera approaches will be examined, including modern architectures such as YOLOv8 and EfficientNet for real-time detection, monocular depth estimation networks like MiDaS and LeReS, and the computational requirements for real-time processing on embedded platforms.

2.3. SLAM Systems Evaluation

This section will present a detailed technical evaluation of Simultaneous Localization and Mapping (SLAM) systems considered for the Tino V2 implementation. ORB-SLAM3 will be examined first, analyzing its support for monocular, stereo, and RGB-D sensor configurations, robustness in dynamic environments through advanced feature matching, and computational requirements that necessitate GPU optimization for real-time performance. The evaluation will cover map persistence capabilities, loop closure detection mechanisms, and integration challenges encountered during development. SVO (Semi-direct Visual Odometry) will be analyzed for its compatibility with fisheye and catadioptric cameras, reduced computational footprint compared to feature-based methods, and performance limitations in textureless environments. The discussion will include practical implementation challenges and compilation issues encountered on ARM64 architectures. RTABMap (Real-Time Appearance-Based Mapping) will be evaluated as the selected SLAM solution, examining its multi-session mapping capabilities, robust map saving and loading functionality, and superior relocalization performance. The analysis will cover integration with the Oak-D Pro camera through the DepthAI library, ROS2 compatibility, and performance characteristics that made it the optimal choice for the Tino V2 platform.

2.4. Technology Selection Rationale

This section will present the systematic decision-making process that led to the final technology stack selection for Tino V2. The evaluation criteria will be established first, including accuracy requirements for social interaction scenarios, computational efficiency constraints of embedded platforms, integration complexity with existing systems, and reliability requirements for sustained operation. For localization technology selection, the analysis will explain why a hybrid approach combining RTABMap SLAM with UWB positioning was chosen over single-technology solutions. The decision process will cover RTABMap's superior map persistence and relocalization capabilities compared to ORB-SLAM3 and SVO, UWB technology's potential for absolute positioning to address SLAM drift issues, and the complementary nature of visual orientation data from SLAM with precise positioning from UWB systems. For human detection technology selection, the rationale for choosing YOLOv11 with TensorRT optimization will be presented, including real-time performance capabilities, accuracy in detecting multiple humans simultaneously, and successful integration with stereo depth data for 3D positioning. The section will address why this approach was preferred over thermal imaging or pure RGB-D solutions, considering Tino's specific operational requirements and physical constraints.

2.5. Hybrid Approach Justification

This section will provide detailed justification for the hybrid localization approach that combines multiple sensing modalities to achieve superior performance compared to individual technologies. The limitations of SLAM-only approaches will be discussed first, including drift accumulation over extended operation periods, relocalization failures in feature-poor environments, and map corruption issues that can compromise long-term operation. Specific examples from the development process will illustrate scenarios where RTABMap exhibited positioning drift up to 1.2 meters, necessitating manual intervention or robot rotation to achieve relocalization. The complementary capabilities of UWB positioning will be explained, demonstrating how centimeter-level absolute positioning addresses SLAM drift issues while maintaining the rich environmental understanding provided by visual SLAM systems. The sensor fusion strategy will be detailed, explaining how RTABMap provides reliable orientation information and environmental mapping while UWB delivers precise global positioning, creating a robust localization system that leverages the strengths of both technologies. Performance comparisons will be presented showing the improved accuracy and reliability achieved through the hybrid approach compared to individual sensor modalities.

2.6. Selected Technology Stack for Tino V2

This section will present the final integrated technology stack selected for the Tino V2 platform, providing a comprehensive overview of how individual components work together to achieve the project objectives. The hardware platform selection will be detailed first, explaining the migration from Raspberry Pi to NVIDIA Orin Nano and the performance benefits this transition enables for real-time SLAM processing, computer vision algorithms, and multi-modal sensor fusion. The Oak-D Pro camera selection will be justified for its stereo depth capabilities, DepthAI library integration, and compatibility with RTABMap SLAM implementation. The localization system architecture will be presented, describing the integration of RTABMap SLAM for visual odometry and mapping with UWB positioning for absolute coordinate reference, including the sensor fusion algorithms that combine these data streams. The human detection pipeline will be detailed, covering YOLOv11 implementation with TensorRT optimization, stereo depth integration for 3D human positioning, and real-time skeleton tracking with 17 key body joints. The software architecture selection will explain the migration to ROS2 for improved modularity, the node-based system design that enables independent development and testing of subsystems, and the communication protocols that facilitate integration with VR systems and external applications.

3 | System Architecture and Software Migration

3.1. Legacy System Analysis and Limitations

This section will provide a comprehensive analysis of the original Tino robot system architecture, establishing the technical foundation that necessitated the migration to Tino V2. The legacy system evaluation will begin with a detailed examination of the Raspberry Pi-based control architecture, including its computational limitations for real-time processing, memory constraints that restricted simultaneous operation of multiple sensing modalities, and processing bottlenecks that prevented implementation of advanced computer vision algorithms. The original software architecture will be analyzed, covering the monolithic Python script design that combined all robot functionalities into single-threaded execution, leading to poor modularity, difficult debugging procedures, and limited scalability for adding new features. The communication system limitations will be discussed, including the lack of standardized message protocols, direct serial communication bottlenecks with Arduino subsystems, and absence of distributed processing capabilities. The sensor integration challenges will be examined, particularly the limited bandwidth for camera data processing, inadequate computational resources for SLAM implementation, and difficulties in achieving synchronized multi-sensor operation. Finally, the section will address reliability and maintenance issues, including system crashes due to resource exhaustion, difficulties in isolating and fixing component failures, and the challenges of remote debugging and system monitoring.

3.2. ROS2 Architecture Design and Implementation

This section will detail the comprehensive ROS2 architecture designed for Tino V2, explaining how the Robot Operating System 2 framework addresses the limitations identified in the legacy system. The ROS2 framework selection rationale will be presented first, covering its advantages in distributed computing, real-time performance capabilities, improved inter-process communication through DDS (Data Distribution Service), and enhanced security features compared to ROS1. The system architecture design principles will be explained, including the modular node-based approach that enables independent development and testing of subsystems, standardized message interfaces that facilitate component integration, and distributed processing capabilities that leverage the Orin Nano's enhanced computational resources. The communication infrastructure will be detailed, covering the publish-subscribe messaging paradigm, quality of service (QoS) policies for reliable data transmission, and the discovery mechanisms that enable automatic node detection and connection. The real-time considerations will be addressed, including deterministic message delivery, priority-based scheduling, and resource allocation strategies that ensure consistent performance for time-critical operations. The development and deployment advantages will be discussed, covering the improved debugging capabilities through ROS2 tools, enhanced logging and monitoring systems, and the simplified integration with external systems and simulation environments.

3.3. Node Structure and Functionality

This section will provide detailed descriptions of the individual ROS2 nodes that compose the Tino V2 system, explaining their specific responsibilities and interactions within the overall architecture. The gamepad_node.py will be examined first, detailing its role in handling Xbox controller input with proper D-input to X-input conversion for Jetson compatibility, the implementation of the pulse-based command system that generates discrete movement commands for VR integration, and the enhanced command processing and error reporting mechanisms that improve control system robustness. The hardware_interface_node.py will be analyzed, covering its management of serial communication with all three Arduino systems (head, base, leg), the implementation of proper device symlinks for consistent Arduino connections, and the comprehensive debugging logs and status monitoring that enable effective system maintenance. The robot_controller_node.py functionality will be detailed, explaining its role as the central coordination node that manages all robot behaviors and movement commands, the implementation of the atomic movement system with 4-state leg and base control, and the synchronization mechanisms that ensure coordinated robot actions. The vr_interface_node.py will be examined, covering its handling of VR system integration and data exchange for Unity communication, the implementation of bidirectional audio communication systems, and the data recording and extraction capabilities that support VR system development and testing.

3.4. Communication Protocols and Message Design

This section will detail the communication infrastructure and message protocols developed for the Tino V2 system, ensuring reliable and efficient data exchange between all system components. The inter-node communication design will be explained first, covering the topic-based messaging system that enables decoupled component interaction, the service-call mechanisms for synchronous operations requiring immediate responses, and the action-based communication for long-running tasks with progress feedback. The custom message definitions will be detailed, including pose and localization messages that carry 3D position and orientation data with timestamp information, human detection messages that contain skeleton joint positions and confidence scores, and VR interface messages that facilitate bidirectional communication with Unity systems. The Arduino communication protocols will be examined, covering the enhanced serial communication protocols that provide reliable command transmission and status feedback, the implementation of command acknowledgment systems that ensure successful command execution, and the error handling mechanisms that detect and recover from communication failures. The data synchronization strategies will be discussed, including timestamp-based alignment of multi-sensor data, buffering mechanisms that handle varying data rates from different sensors, and the quality of service configurations that prioritize critical data streams while ensuring overall system stability.

3.5. Integration with External Systems

This section will explain how the ROS2 architecture facilitates integration with external systems and development tools, enhancing the overall capability and research value of the Tino V2 platform. The VR system integration will be detailed first, covering the ROS-TCP-Endpoint implementation that provides a communication bridge between ROS2 and Unity, the enhanced error handling mechanisms that ensure robust VR communication, and the data recording systems that capture comprehensive robot state information for VR development and analysis. The monitoring and debugging capabilities will be discussed, covering the comprehensive logging systems that track all node activities and system events, the diagnostic tools that provide real-time system health monitoring, and the remote access capabilities that enable development and troubleshooting via VNC connections. The extensibility features will be addressed, explaining how the modular architecture enables easy addition of new sensors and capabilities, the standardized interfaces that facilitate integration of third-party components, and the configuration management systems that allow dynamic parameter adjustment without system restart.

3.6. Migration Benefits and System Improvements

This section will quantify and analyze the improvements achieved through the migration from the legacy Raspberry Pi system to the ROS2-based Orin Nano architecture. The performance improvements will be detailed first, including the computational performance gains that enable real-time SLAM processing, computer vision algorithms, and multi-sensor fusion, the memory management improvements that allow simultaneous operation of multiple demanding processes, and the reduced latency in sensor data processing and command execution. The reliability enhancements will be examined, covering the improved system stability through modular architecture that isolates component failures, the enhanced error handling and recovery mechanisms that maintain system operation during partial failures, and the diagnostic capabilities that enable proactive maintenance and issue identification. The development efficiency improvements will be discussed, including the reduced development time for new features through standardized interfaces and modular design, the improved debugging capabilities that enable rapid issue identification and resolution, and the enhanced testing procedures that allow independent validation of system components. The operational advantages will be addressed, covering the simplified system startup and shutdown procedures, the improved remote monitoring and control capabilities, and the enhanced data logging and analysis tools that support research activities. Finally, the scalability benefits will be presented, explaining how the new architecture supports future expansion with additional sensors and capabilities, enables distributed processing across multiple computing platforms, and facilitates integration with cloud-based services and external research systems.

4 | SLAM Implementation and Sensor Fusion

4.1. RTABMap Integration with Oak-D Pro Camera

This section will detail the comprehensive implementation of RTABMap (Real-Time Appearance-Based Mapping) SLAM system with the Oak-D Pro camera, establishing the foundation for Tino V2's localization capabilities. The Oak-D Pro camera integration will be explained first, covering the DepthAI library implementation that provides seamless access to stereo depth data, the ROS2 wrapper configuration that publishes synchronized color and depth image streams, and the camera calibration procedures that ensure accurate depth estimation and feature detection. The RTABMap configuration process will be detailed, including the parameter optimization for indoor environments, memory management settings that enable long-term operation without performance degradation, and the feature detection and matching algorithms that provide robust visual odometry in dynamic social interaction scenarios. The stereo vision implementation will be examined, covering how the Oak-D Pro's dual camera system provides depth information for feature triangulation, the baseline calibration that ensures accurate 3D point cloud generation, and the integration with RTABMap's visual-inertial odometry algorithms. The real-time performance optimization will be discussed, including the computational load balancing between feature extraction and map building processes, the memory allocation strategies that prevent system crashes during extended mapping sessions, and the parameter tuning that achieves optimal performance on the Orin Nano platform.

4.2. SLAM Mapping and Localization Modes

This section will explain the dual operational modes implemented in the Tino V2 system, enabling both map creation and autonomous navigation capabilities. The mapping mode implementation will be detailed first, covering the launch file configuration (rtab_mapping.launch.py) that initializes all necessary nodes for map creation, the real-time visualization capabilities that allow monitoring of map building progress, and the landmark placement strategies that improve map quality and relocalization reliability. The map building process will be examined, including the loop closure detection mechanisms that ensure map consistency, the keyframe selection algorithms that optimize memory usage while maintaining map quality, and the feature database management that enables efficient storage and retrieval of visual landmarks. The localization mode implementation will be explained, covering the launch file configuration (rtab_localization.launch.py) that loads existing maps and initializes positioning systems, the relocalization algorithms that enable the robot to determine its position within a previously created map, and the continuous tracking mechanisms that maintain accurate positioning during navigation. The mode switching procedures will be detailed, including the map saving and loading protocols that ensure data persistence, the system state management that enables seamless transitions between mapping and localization modes, and the parameter configuration changes required for optimal performance in each operational mode.

4.3. Initial SLAM-Only System Limitations and Drift Issues

This section will present a comprehensive analysis of the limitations discovered during initial testing of the SLAM-only localization approach, providing the technical justification for implementing the hybrid sensor fusion system. The drift accumulation problems will be documented first, including specific measurement data showing position errors of up to 1.2 meters during extended operation, the systematic analysis of error sources including visual odometry drift and map inconsistencies, and the environmental factors that contribute to localization degradation such as lighting changes and repetitive textures. The relocalization challenges will be examined, covering scenarios where RTABMap failed to correctly determine robot position within existing maps, the feature-poor environments that caused tracking failures, and the manual intervention requirements (robot rotation) needed to achieve successful relocalization. The performance testing methodology will be detailed, including the four-position testing protocol implemented to quantify localization accuracy, the repeated measurement procedures that revealed consistency issues, and the statistical analysis of position errors that demonstrated the need for absolute positioning reference. The specific failure modes will be analyzed, covering map corruption events that required complete map reconstruction, tracking loss scenarios that occurred near walls or in areas with insufficient visual features, and the computational resource limitations that affected real-time performance during intensive mapping operations.

4.4. UWB Positioning System Implementation

This section will detail the Ultra-Wideband (UWB) positioning system integration that provides absolute positioning reference to complement the visual SLAM system. The UWB hardware implementation will be explained first, covering the anchor placement strategy that ensures optimal coverage of the operating environment, the calibration procedures that establish accurate position references, and the tag integration with the Tino robot platform that minimizes interference with other systems. The positioning algorithm implementation will be detailed, including the multilateration techniques that calculate 3D position from multiple anchor measurements, the Non-Line-of-Sight (NLOS) mitigation strategies that improve accuracy in complex indoor environments, and the filtering algorithms that reduce measurement noise and provide stable position estimates. The coordinate system alignment will be examined, covering the transformation procedures that align UWB coordinates with the SLAM coordinate frame, the map offset implementation that enables rotational correction of SLAM maps, and the calibration protocols that ensure consistent positioning across different operational sessions. The real-time performance characteristics will be analyzed, including the update rates achieved by the UWB system, the latency measurements that demonstrate suitability for real-time control applications, and the accuracy evaluation that shows centimeter-level positioning precision under optimal conditions.

4.5. Sensor Fusion Between RTABMap Orientation and UWB Positioning

This section will present the sophisticated sensor fusion approach that combines the complementary strengths of visual SLAM and UWB positioning to achieve superior localization performance. The fusion algorithm design will be explained first, covering the Extended Kalman Filter (EKF) implementation that optimally combines position and orientation data from multiple sources, the state estimation procedures that maintain accurate robot pose estimates, and the uncertainty quantification methods that provide confidence measures for navigation decisions. The data synchronization implementation will be detailed, including the timestamp alignment procedures that ensure temporal consistency between sensor measurements, the interpolation algorithms that handle different update rates from SLAM and UWB systems, and the buffering mechanisms that maintain data integrity during temporary sensor outages. The orientation and position separation strategy will be examined, covering how RTABMap provides reliable orientation information while UWB delivers absolute position data, the coordinate transformation procedures that maintain consistency between different sensor coordinate frames, and the validation algorithms that detect and reject outlier measurements. The adaptive fusion parameters will be discussed, including the dynamic weighting strategies that adjust fusion coefficients based on sensor reliability, the fault detection mechanisms that identify sensor malfunctions or degraded performance, and the graceful degradation procedures that maintain operation when individual sensors fail.

4.6. Final Hybrid Localization System Performance

This section will present comprehensive performance evaluation of the final hybrid localization system, demonstrating the improvements achieved through sensor fusion compared to individual sensing modalities. The accuracy evaluation will be detailed first, including quantitative measurements comparing SLAM-only, UWB-only, and hybrid system performance, statistical analysis of position errors showing significant improvement in the fused system, and repeatability testing that demonstrates consistent performance across multiple operational sessions. The specific performance data will be presented, covering the four-position testing results that show centimeter-level accuracy with the hybrid system, the position consistency measurements that demonstrate reduced drift compared to SLAM-only operation, and the orientation accuracy evaluation that validates the continued use of visual odometry for heading estimation. The operational reliability improvements will be examined, including the reduced need for manual relocalization procedures, the improved performance in challenging environments with poor visual features, and the enhanced system stability during extended autonomous operation. The computational performance analysis will be discussed, covering the processing load distribution between SLAM and UWB systems, the real-time performance characteristics that meet the requirements for responsive robot control, and the memory usage optimization that enables continuous operation without system degradation. Finally, the system robustness evaluation will be presented, including fault tolerance testing that demonstrates graceful degradation when individual sensors fail, environmental adaptability testing that shows consistent performance across different lighting and structural conditions, and long-term stability evaluation that validates the system's suitability for extended autonomous operation in social robotics applications.

5 | Hardware Redesign and Mechanical Improvements

5.1. Kinematic Base Upgrade from Omnidirectional to Differential Drive

This section will detail the comprehensive redesign of Tino's mobility system, transitioning from the problematic omnidirectional Triksta base to a robust differential drive architecture. The limitations of the original omnidirectional system will be analyzed first, covering the mechanical failures experienced with the omniwheel rollers that became squared due to Tino's 20kg weight, the dragging issues with the rear wheel that occurred during forward and turning movements, and the unreliable motor performance under the sustained loads required for social robot operation. The differential drive design rationale will be explained, including the simplified kinematics that eliminate the complexity of omnidirectional control while maintaining adequate maneuverability for social interaction scenarios, the improved weight distribution that reduces stress on individual components, and the enhanced reliability achieved through proven mechanical design principles. The mechanical implementation will be detailed, covering the construction of the T-structure using aluminum Item profiles that provide a dynamic and adjustable framework, the motor mounting system modifications required to accommodate the new differential drive configuration, and the wheel positioning optimization that achieves proper balance and traction for the robot's operational requirements. The control system adaptation will be examined, including the implementation of custom PID (Proportional-Integral-Derivative) controllers specifically designed for differential drive kinematics, the motor driver upgrade to the more powerful MDD10A units that can handle increased loads, and the command interface modifications that maintain compatibility with existing movement control systems while improving performance and reliability.

5.2. Power Supply System Redesign for Orin Nano

This section will present the comprehensive power system redesign required to support the NVIDIA Orin Nano platform and associated high-performance components. The power requirements analysis will be detailed first, covering the Orin Nano's 19V DC input requirement and power consumption characteristics that reach up to 2A during maximum computational load, the additional power needs for the Oak-D Pro camera and onboard router systems, and the total system power budget that necessitated complete redesign of the legacy Raspberry Pi power architecture. The DC-DC converter implementation will be explained, including the selection and testing of the Oumefar 12V to 19V step-up converter that provides stable power delivery, the power efficiency analysis that demonstrates optimal battery utilization, and the thermal management considerations that ensure reliable operation under sustained loads. The battery system optimization will be examined, covering the consolidation from four separate battery systems to three integrated power sources, the 5200mAh 80C 11.1V 57.72Wh battery specification that provides approximately 1.37 hours of operation at maximum load, and the realistic operational time estimates of 2-3 hours under typical social interaction scenarios. The cable harness redesign will be detailed, including the removal of legacy USB-A and USB-C connections that were used for Raspberry Pi power delivery, the implementation of proper 12V input distribution and 19V DC jack connectivity, and the integration of the 12V to 5V converter that powers the onboard router and camera systems independently, providing flexibility for future system expansions and reducing the computational load on the main platform.

5.3. Stewart Platform Head Mechanism Improvements

This section will document the iterative design improvements made to Tino's Stewart platform head mechanism to address reliability issues and enhance performance under operational loads. The original system limitations will be analyzed first, covering the servo axis misalignment problems that created excessive stress on servo motors during head movements, the structural flex issues in the connecting arms that caused mechanical instability and reduced precision, and the repeated arm failures that occurred due to inadequate load distribution and material selection. The first design iteration will be detailed, including the servo axis alignment improvement that redirected forces through the head structure rather than the servo mechanisms, the 3D printed PLA arm replacement with enhanced geometry for improved load distribution, and the initial performance evaluation that showed reduced servo stress but continued structural flex issues. The final design implementation will be examined, covering the adoption of rod end (heim joints) on both ends of each Stewart platform arm to eliminate binding and allow free rotation, the combination of 3D printed components with metal heim joints that provides optimal balance between cost and performance, and the mechanical trade-offs including acceptable head wobble during stationary periods that may actually enhance the robot's expressive capabilities. The performance validation will be discussed, including load testing that demonstrates improved reliability under operational conditions, the movement precision evaluation that shows maintained accuracy despite the mechanical improvements, and the longevity testing that validates the enhanced design's suitability for extended social interaction scenarios.

5.4. Camera Integration and Mounting Solutions

This section will detail the comprehensive camera integration system developed to address the unique challenges of mounting sophisticated sensing equipment within Tino's soft fabric structure. The mounting system design will be explained first, covering the tripod-based camera support system that provides stable mounting for the Oak-D Pro camera, the bracket design that ensures proper camera alignment and minimizes vibration during robot movement, and the integration with the existing Stewart platform head that allows synchronized camera and head movements. The fabric integration challenges will be analyzed, including the camera visibility requirements that necessitate fabric modification without compromising Tino's aesthetic appeal, the heat dissipation needs of the Oak-D Pro camera that require ventilation considerations, and the protection requirements that shield sensitive camera components from physical damage during social interactions. The camera shell development will be detailed, covering the custom enclosure design that provides protection while maintaining cooling airflow, the velcro attachment system that secures fabric positioning without interfering with camera operation, and the mesh covering implementation that conceals the camera from casual observation while maintaining full operational capability. The field of view optimization will be examined, including the fabric positioning strategies that prevent interference with camera sensing, the testing procedures that validate optimal camera performance under various fabric configurations, and the reliability evaluation that ensures consistent operation throughout extended social interaction sessions.

5.5. Audio System Integration

This section will present the comprehensive audio system implementation that enables bidirectional communication capabilities for VR integration and enhanced human-robot interaction. The hardware component selection will be detailed first, covering the iTalk-01 omnidirectional microphone specification and mounting considerations within the fabric head structure, the speaker system selection and placement optimization that provides clear audio output without interfering with other robot systems, and the audio processing requirements that enable real-time communication with VR systems. The integration challenges will be analyzed, including the acoustic isolation needed to prevent feedback between microphone and speakers, the cable routing through the robot's structure that maintains mechanical flexibility while ensuring reliable connections, and the power management considerations that integrate audio components with the overall system power budget. The software implementation will be examined, covering the audio_node.py and audio_loopback.py ROS2 nodes that handle audio capture and playback, the bidirectional communication protocols that enable seamless VR audio integration, and the audio processing algorithms that ensure high-quality sound transmission and reception. The performance validation will be discussed, including audio quality testing that demonstrates suitable performance for human-robot communication, latency measurements that verify real-time communication capabilities, and integration testing that validates seamless operation with the VR system and overall robot behavior control.

5.6. Mechanical Reliability Improvements and Testing

This section will document the systematic approach to identifying and resolving mechanical reliability issues that affected the legacy Tino system and the validation procedures used to ensure improved performance in Tino V2. The failure analysis methodology will be explained first, covering the systematic documentation of component failures during development and testing, the root cause analysis procedures that identified design weaknesses and operational stress factors, and the prioritization of improvements based on criticality and impact on robot operation. The wheel system improvements will be detailed, including the plastic wheel hub failure analysis that led to hot glue reinforcement as an interim solution, the tire de-beading issues caused by robot weight and the hot glue filling solution that restored proper tire-to-rim interface, and the wheel bumper implementation that prevents fabric entanglement during robot movement. The structural enhancements will be examined, covering the aluminum profile framework that provides improved rigidity and adjustability compared to the original design, the motor bracket modifications that ensure proper alignment and reduce mechanical stress, and the fastener and connection improvements that enhance overall system reliability. The validation testing procedures will be discussed, including the systematic load testing that verifies component performance under operational conditions, the endurance testing that demonstrates sustained operation capabilities, and the performance monitoring that tracks system health during extended operational periods. Finally, the preventive maintenance protocols will be presented, covering the inspection procedures that enable early detection of potential issues, the component replacement schedules that prevent unexpected failures, and the documentation systems that track system performance and maintenance history for continuous improvement of mechanical reliability.

6 | Human Detection and Pose Estimation

6.1. YOLOv11 Pose Detection Implementation with TensorRT Optimization

This section will detail the implementation of YOLOv11 pose detection system optimized for real-time performance on the NVIDIA Orin Nano platform using pre-trained models. The YOLOv11 architecture selection will be explained first, covering the advantages of using the latest YOLO iteration for pose estimation tasks, including improved accuracy in detecting multiple humans simultaneously and optimized network architecture that balances detection accuracy with computational efficiency for embedded platforms. The pre-trained model utilization will be detailed, including the selection of the yolo11n-pose.pt model that provides an optimal balance between accuracy and computational requirements, the model format conversion from PyTorch (.pt) to ONNX (.onnx) format for cross-platform compatibility, and the final optimization to TensorRT engine (.engine) format that maximizes inference performance on the Orin Nano's GPU. The TensorRT optimization process will be examined, covering the engine generation procedures that optimize the neural network for the specific hardware platform and the memory allocation strategies that ensure efficient GPU utilization during real-time operation. The implementation architecture will be discussed, including the ROS2 node design that subscribes to camera topics from the Oak-D Pro and publishes human detection results, and the message publishing system that provides skeleton joint information with confidence scores for other system components.

6.2. Stereo Depth Integration for 3D Human Positioning

This section will present the integration of stereo depth information with 2D pose detection to achieve 3D human positioning capabilities using the Oak-D Pro camera system. The depth data utilization will be detailed first, covering how the stereo camera system provides depth information at detected keypoint locations, the depth value extraction process that determines 3D coordinates for each detected joint, and the coordinate system transformation from camera frame to robot coordinate frame. The 3D positioning methodology will be explained, including the process of combining 2D joint detections with corresponding depth values to create 3D skeleton representations and the real-time processing requirements that maintain system responsiveness while providing human positioning information. The practical implementation will be discussed, including how depth measurement works at varying distances and the integration with the robot's localization system to provide human positions relative to the robot's coordinate frame.

6.3. Real-time Skeleton Tracking with 17 Key Body Joints

This section will detail the skeleton tracking implementation that extracts and processes 17 standard COCO keypoints for human posture detection. The keypoint detection framework will be explained first, covering the 17 keypoints detected by YOLOv11 including nose, eyes, ears, shoulders, elbows, wrists, hips, knees, and ankles, and the confidence scoring system that indicates detection reliability for each joint. The data processing pipeline will be detailed, including the extraction of keypoint coordinates and confidence scores from YOLOv11 output, the organization of joint information into structured skeleton representations, and the real-time publishing of skeleton data through ROS2 topics. The message format and data flow will be discussed, including the custom ROS2 message structures that transmit skeleton data with timestamps and the integration with other system components that can utilize human pose information for robot operation and VR data recording.

6.4. Performance Optimization and Real-time Operation

This section will present the optimization strategies implemented to achieve real-time performance of the human detection system on the Orin Nano platform. The computational optimization techniques will be detailed first, covering the TensorRT engine utilization that maximizes GPU inference performance and the memory management strategies that prevent resource exhaustion during continuous operation. The real-time performance characteristics will be explained, including the frame rate capabilities achieved by the optimized system and the processing latency from camera input to pose detection output. The system integration optimization will be examined, covering how the pose detection system operates alongside other robot functions including SLAM, localization, and movement control without creating performance bottlenecks. The practical performance evaluation will be discussed, including testing under various operational scenarios and system stability during extended operation periods.

6.5. Integration with System Architecture

This section will detail the integration of human detection with Tino's overall system architecture and coordination with other robot components. The data flow architecture will be explained first, covering how human pose detection results are published through ROS2 topics and made available to other system components including robot controller nodes and navigation systems. The system coordination will be discussed, including how pose detection operates in parallel with other robot functions such as localization, movement control, and audio processing without creating performance bottlenecks. The ROS2 integration implementation will be examined, covering the message publishing system that provides skeleton joint information with timestamps and the node architecture that ensures reliable data transmission to other system components. Finally, the practical benefits will be addressed, covering how real-time human detection enhances the robot's operational awareness and enables improved human-robot interaction capabilities through better understanding of human presence and positioning.

7 | VR Integration and Atomic Movement System

7.1. VR System Architecture and Unity Communication

This section will detail the comprehensive VR integration system that enables remote control and monitoring of Tino through Unity-based VR environments. The VR interface architecture will be explained first, covering the ROS2 `vr_interface_node` that serves as the central communication bridge between the robot's ROS2 system and external Unity applications, and the UDP communication protocol that provides real-time bidirectional data exchange for low-latency VR interaction. The Unity integration capabilities will be detailed, including the message structures for sending robot control commands from VR to ROS2 topics, the data reception system that provides robot pose, human detection, and audio information to Unity for visualization and interaction, and the networking configuration that enables flexible deployment across different network environments. The communication monitoring system will be examined, covering the configurable send rates for pose and skeleton data transmission, the health monitoring that tracks communication status and detects connection failures, and the message ordering system that ensures reliable data delivery and duplicate detection. The VR data recording functionality will be discussed, including the comprehensive recording system that captures all VR-relevant data streams for offline analysis.

7.2. Atomic Movement System Design and 4-State Control Architecture

This section will present the revolutionary atomic movement system designed specifically for natural VR interaction, replacing the previous continuous control scheme with discrete, completion-guaranteed movements. The 4-state control framework will be explained first, covering the unified state architecture applied to both leg and base controllers where state 0 represents idle/resting position, state 1 implements expressive "little push" movements for attention-getting behaviors, state 2 provides timing synchronization cycles, and state 3 executes atomic movements that must complete before new commands can be processed. The leg controller implementation will be detailed, including the state 1 optimized 3-phase movement (50% forward extension, 5% pause, 45% return), the state 2 forward extension to maximum reach with position locking mechanisms, and the state 3 return-to-neutral movement with button-press completion detection. The base controller design will be examined, covering the state 1 rapid forward-backward sequence for expressive pointing behaviors, the state 2 timing cycle that provides 1.5-second synchronization delay, and the state 3 atomic movements including forward translation and left/right rotation operations, each with 1.7-second execution duration. The synchronization architecture will be discussed, including the sophisticated locking system that prevents base state 3 execution until leg state 2 completion, and the pending command system that stores VR commands during ongoing operations and automatically executes them upon completion.

7.3. Pulse-Based Command System for VR Integration

This section will detail the pulse-based command architecture that ensures perfect correspondence between VR user actions and physical robot movements. The pulse generation system will be explained first, covering the replacement of continuous signal transmission with discrete 3-cycle command pulses that automatically return to idle state, ensuring each VR interaction triggers exactly one complete robot movement cycle. The gamepad integration modifications will be detailed, including the removal of analog joystick control in favor of discrete button-based state commands, and the implementation of pulse timing that provides consistent command duration regardless of user input duration. The VR command processing will be examined, covering the UDP packet structure that transmits head control data (pitch, pan, tilt), base movement commands (state and angular direction), and audio parameters (volume and orientation), all synchronized with message ordering for reliable delivery. The atomic guarantee system will be discussed, including the movement completion assurance that prevents partial operations, the state machine locks that maintain movement integrity, and the natural interaction flow that ensures VR users always observe complete robot actions rather than interrupted movements. The timing optimization will be addressed, covering the precise 1.5-second state 2 timing cycle, the 1.7-second state 3 movement duration, and the synchronization mechanisms that coordinate multi-component movements for realistic dragging simulation.

7.4. Unity-ROS2 Communication Protocol and Message Structures

This section will present the comprehensive communication protocol designed for robust Unity-VR to ROS2 integration with optimal performance and reliability. The UDP communication architecture will be explained first, covering the multi-port configuration with port 5005 for incoming VR commands, port 5006 for outgoing robot pose data, and port 5007 for human skeleton transmission, enabling parallel data streams without interference. The incoming message format will be detailed, including the 32-byte VR command packets containing 3 floats for head control (pitch, pan, tilt), 2 integers for base commands (state 0–3, angular direction $-1/0/1$), 2 values for audio control (volume and orientation), and 1 integer for message ordering to detect lost or duplicate packets. The outgoing data structures will be examined, covering the 24-byte robot pose packets with position and orientation data fused from UWB and RTAB-Map systems, and the 208-byte skeleton packets containing exactly 17 COCO-format joints with consistent 3D coordinates for missing or occluded body parts. The configurable transmission rates will be discussed, including independent control of pose data frequency (default 10Hz), skeleton data frequency (default 10Hz), and expected incoming command rate (default 25Hz) to optimize performance for different network conditions and VR application requirements. The monitoring and debugging capabilities will be addressed, covering the comprehensive logging system that tracks communication health, the rate validation that ensures expected data flow, and the error detection mechanisms that identify connection problems and provide detailed diagnostic information for system maintenance.

7.5. Bidirectional Audio Communication and Spatial Processing

This section will detail the advanced audio communication system that enables natural voice interaction between VR users and the physical robot environment. The audio data flow architecture will be explained first, covering the microphone input processing that captures robot-side audio and transmits it to VR systems through ROS2 topics, the VR audio reception that provides spatial audio information with volume and orientation parameters for immersive sound positioning, and the bidirectional communication that enables real-time voice interaction between VR users and people in the robot's physical environment. The audio processing implementation will be detailed, including the 16-bit PCM audio sample handling through Int16MultiArray message structures, the real-time audio streaming that maintains low latency for natural conversation flow, and the volume and orientation control system that allows VR applications to adjust audio characteristics based on virtual positioning and interaction context. The spatial audio integration will be examined, covering the orientation parameter system that provides directional audio information in degrees, the volume control mechanisms that enable distance-based audio attenuation simulation, and the Unity integration capabilities that support immersive audio experiences in VR environments. The practical applications will be discussed, including the human-robot interaction enhancement through voice communication, the remote presence capabilities that allow VR users to participate in physical environment conversations, and the research data collection features that record audio interactions for analysis of human-robot communication patterns and social interaction behaviors.

7.6. VR Data Recording and Research Integration

This section will present the comprehensive VR data recording system designed for research applications and offline VR development. The data recording architecture will be explained first, covering the `vr_data_recorder_node` that subscribes to all VR-relevant topics including robot pose, human detection, skeleton tracking, and audio streams, the SQLite database storage system that efficiently captures timestamped message data for comprehensive interaction analysis, and the recording control services that enable start/stop functionality for targeted data collection sessions. The Unity integration tools will be detailed, including the data extraction utilities that convert ROS2 message data into Unity-compatible JSON formats, the offline playback capabilities that enable VR development and testing without requiring live robot connection, and the message structure preservation that maintains full fidelity of robot sensor data for accurate VR simulation. The research applications will be examined, covering the human-robot interaction analysis enabled by synchronized recording of human pose detection, robot movements, and audio communication, the VR user behavior studies that analyze interaction patterns and command sequences, and the system performance evaluation that tracks communication rates, latency, and reliability metrics across different operational scenarios. The development workflow benefits will be discussed, including the VR application testing capabilities that use recorded data for consistent development environments, the debugging tools that enable analysis of communication problems and timing issues, and the educational applications that provide realistic robot interaction data for VR training and demonstration purposes. Finally, the extensibility features will be addressed, covering the modular recording system that can be configured for specific research requirements, the data format compatibility that supports integration with external analysis tools, and the scalability considerations that enable recording of extended interaction sessions for longitudinal studies.

8 | System Evaluation, Future Work and Conclusions

8.1. Localization System Performance Evaluation

This section will present the evaluation results of Tino's localization systems, comparing pure SLAM performance with the implemented UWB sensor fusion approach. The RTAB-Map SLAM baseline evaluation will be detailed first, covering the systematic testing conducted at four fixed positions with multiple iterations, the significant drift issues discovered with maximum deviations of 1.20 meters, and the need for manual relocalization through spinning movements that proved impractical for VR users without technical expertise. The UWB sensor fusion implementation assessment will be examined, including the positioning system integration that provides improved accuracy with position coordinates showing better consistency across multiple trials, the RTAB-Map orientation preservation that maintained reliable heading information, and the significant improvement in positioning stability with the combined UWB position and SLAM orientation approach. The experimental methodology will be discussed, covering the controlled testing environment with marked floor positions for measurement points, the multiple iteration protocol that provided comparison data, and the systematic data collection that revealed both system capabilities and limitations. The performance comparison analysis will be addressed, including position accuracy measurements showing UWB coordinates with improved consistency compared to pure SLAM, orientation reliability maintained through RTAB-Map integration, and the practical implications for VR integration requiring more reliable positioning without manual intervention.

8.2. System Limitations and Identified Challenges

This section will provide a comprehensive analysis of the identified system limitations and technical challenges encountered during development and testing. The localization system constraints will be detailed first, covering the RTAB-Map dependency on visual features that requires careful environment preparation with sufficient landmarks, the drift accumulation issues that necessitated the UWB sensor fusion implementation, and the map alignment challenges that require manual angle offset adjustments for proper Unity integration. The hardware reliability concerns will be examined, including the mechanical stress points identified during testing such as wheel hub failures requiring temporary repairs, the power system limitations that affect extended operation capabilities, and the component integration challenges that impact overall system robustness. The computational resource limitations will be discussed, covering the NVIDIA Orin Nano platform constraints that require careful optimization of concurrent processes, the memory management requirements for simultaneous SLAM, pose detection, and VR communication operations, and the thermal considerations during extended operation periods. The network communication challenges will be addressed, including the UDP packet loss scenarios that require robust error handling, the bandwidth limitations when transmitting high-frequency pose and skeleton data, and the latency variations that affect VR user experience quality. The VR system integration constraints will be covered, including the Unity development complexity for implementing robust robot communication, the synchronization challenges between virtual and physical environments, and the user experience limitations when technical expertise is required for system recovery or troubleshooting.

8.3. Future Improvements and Research Directions

This section will outline the comprehensive roadmap for future system enhancements and research opportunities identified through the evaluation process. The localization system enhancements will be detailed first, covering the potential integration of additional UWB anchors for improved positioning accuracy and coverage area expansion, the exploration of advanced sensor fusion techniques combining IMU data with existing UWB and visual systems, and the development of automatic map alignment algorithms that eliminate manual angle offset requirements. The mechanical system improvements will be examined, including the replacement of failure-prone components with more robust alternatives, the implementation of predictive maintenance capabilities through sensor monitoring, and the exploration of advanced actuator systems that provide smoother movement profiles and reduced mechanical stress. The computational optimization opportunities will be discussed, covering the potential migration to more powerful embedded platforms as they become available, the implementation of distributed processing architectures that leverage multiple computational units, and the development of adaptive resource management systems that dynamically allocate processing power based on operational requirements. The VR integration advancement possibilities will be addressed, including the development of more sophisticated interaction paradigms that leverage advanced pose detection capabilities, the implementation of haptic feedback systems that enhance user immersion and control precision, and the exploration of multi-user VR environments that support collaborative robot interaction scenarios. The research application extensions will be covered, including the development of comprehensive datasets for human-robot interaction research, the implementation of machine learning systems that adapt robot behavior based on user interaction patterns, and the exploration of social robotics applications that leverage the established VR integration framework. Finally, the long-term vision will be presented, covering the potential evolution toward fully autonomous social interaction capabilities, the integration with broader smart environment systems, and the development of replicable platforms that enable wider adoption of VR-integrated social robotics research.

8.4. Conclusions and Lessons Learned

This section will synthesize the key findings from the Tino V2 development process, highlighting significant achievements and valuable insights for future robotics research. The technical achievement summary will be presented first, covering the successful migration from legacy Raspberry Pi architecture to modern ROS2-based systems on NVIDIA Orin Nano, the implementation of sensor fusion combining UWB positioning with RTAB-Map orientation that addresses localization drift issues, and the development of atomic movement systems that enable natural VR interaction through discrete, completion-guaranteed operations. The methodological insights will be detailed, including the importance of systematic testing protocols for identifying system limitations like SLAM drift issues, the value of modular architecture design that enables independent development of localization, movement, detection, and communication subsystems, and the critical role of practical testing in revealing real-world challenges such as mechanical reliability concerns. The interdisciplinary integration lessons will be examined, covering the challenges and benefits of combining computer vision, robotics, networking, and VR technologies in a cohesive system, the importance of maintaining real-time performance requirements across all subsystems, and the value of comprehensive documentation and monitoring systems for troubleshooting complex multi-component interactions. The research contribution significance will be discussed, including the advancement of VR-integrated social robotics through practical implementation of bidirectional communication systems, the development of atomic movement architectures that ensure predictable robot behavior for remote users, and the demonstration of sensor fusion approaches that combine complementary positioning technologies. The broader implications will be addressed, covering the potential impact on social robotics research through demonstrated VR integration capabilities, the contribution to human-robot interaction studies through comprehensive data recording and analysis tools, and the advancement of embedded robotics development through optimization of complex algorithms on resource-constrained platforms. Finally, the future outlook will be presented, covering the foundation established for advanced social interaction research, the potential for broader adoption of VR-integrated robotics platforms, and the continued evolution toward more sophisticated and accessible human-robot interaction systems that bridge physical and virtual environments effectively.

Bibliography

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Acknowledgements

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