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Safety-Centric Layered Architecture for a Biped Exoskeleton

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Abstract: Lower-limb exoskeletons integrate mechanical, elec trical, and software technologies to enable interaction with the external environment in a safety-critical context. These systems require real-time response, functional safety, and scalability. This paper introduces a layered sensor-actuator abstraction designed to decouple hardware-dependent services from high-level gait control logic. The proposed architecture comprises four layers: Microcontroller Abstraction (MCAL), Electronic Component Abstraction (ECAL), generic services, and the application layer. It incorporates a dual-tier diagnostic and graded protection mechanisms, achieving deterministic sensor-to-actuator latency. This approach facilitates rapid feature iteration, supports pre dictive torque assistance, and enables cloud-based rehabilitation analytics, adhering to ISO 13482 and IEC 61508 safety standards.

Keywords: Exoskeleton, Architecture, Abstraction, Sensor, Actuator, Signal Conditioning, Functional Safety, Diagnosis, Protection

1. Introduction

Modern lower limb exoskeletons integrate mechanics, high bandwidth drives, and distributed sensing [1], [2]. However, most firmware blends hardware access with gait logic, hin dering certification and reuse. Early modular attempts such as FlexSEA [3], [4] externalized safety, forcing developers to juggle two code bases. Building on previous Internet of Things (IoT) abstraction work [5], [6], [7], we extend layered design principles to wearable robotics critical to safety. This approach relocates safety inside the stack without sacrificing latency, inspired by Automotive Savety Integrity Level (ASIL) patterns [8], [9].

This paper introduces a design concept for an architectural approach to sensor-actuator abstraction for a biped exoskele ton. The development of such a system requires the integration of mechanical, electrical, and software engineering disciplines to enable real-time interaction with the environment. The diversity of technologies involved calls for a structured so lution that can coordinate and abstract core functions while supporting mobility assistance and human augmentation.

The proposed architecture achieves architectural separation between heterogeneous hardware and high-level control logic, embedding functional safety mechanisms, and supporting ad vanced gait algorithms. Integrates diagnosis and protection loops comparable to FlexSEA [3] and stimulation-driven con trollers [10], while adhering to ISO 13482 safety constraints. This layered abstraction confines hardware heterogeneity to well-defined interfaces, allowing independent iteration by elec tronics and control teams and facilitating rapid hardware swaps and AI-based control integration [11].

2. Exoskeleton architectural design

Due to the diverse technological requirements of exoskele ton systems, a unified architecture is needed to manage the complexity of the component level and expose standardized interfaces to higher-level control logic. Sensors and actuators represent the essential interface with the physical world. A lower limb exoskeleton, designed as a wearable mechatronic platform, aims to assist human movement and improve mobil ity. It targets both rehabilitation and enhancement scenarios. The approach must consider this variety of technologies, abstract from it, and provide the upper levels of the system with interfaces for interaction with the environment. Sensors and actuators are essential components for the interaction with the environment. A lower limb exoskeleton is a wearable mechatronic device that supports and enhances leg movements. It helps people with mobility impairments and/or increases the physical capabilities of users. System Architecture is a generic embedded system structure organized in layers to support modular development and systematic interaction [5], [12]. Analog joysticks, buttons, and sensors worn on the body are used to capture user input and intentions. The system architecture diagram is shown in Fig.1.

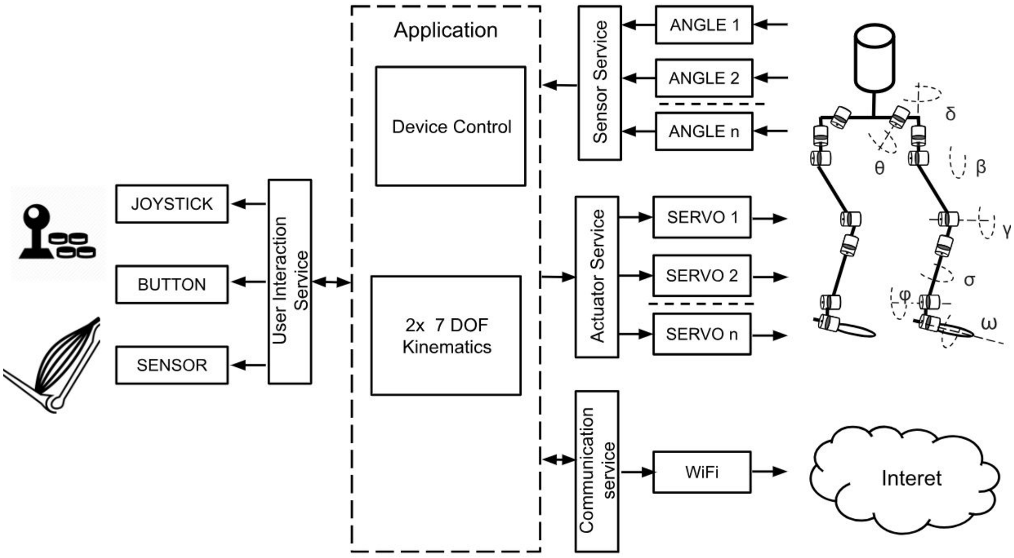

Figure 1. Exoskeleton System Architecture and interaction do mains: User, Environment, and Network.

The application components include motion control algo rithms and kinematic models, with increasing use of intelligent methods. The system is divided into communication modules, sensor–actuator handlers, and user interface components. All operate using layered abstractions to ensure the separation of concerns.

Human–Machine Interface (HMI) integrates a two-axis thumb joystick, tactile buttons, body-mounted inertial sensors (IMUs), and electromyography (EMG) sensors to capture user inputs and intentions [13]. The joystick provides continuous velocity references, while the buttons enable mode selection. IMUs track trunk inclination and EMG sensors detect muscle activity, enhancing usability and interaction with the system. This combination aligns with trends in soft bioelectronics [11] and Robot Operating System (ROS) -based teleoperation [14], [15]. The HMI design ensures intuitive control and supports seamless integration into the layered architecture, following the gateway abstraction principles outlined in [7].

Environment Interaction is facilitated through servomotors and position sensors, which control joint movements and pro vide feedback. The system measures joint torques, velocities, and external contact forces using on-board torque sensors. This interaction relies on seven brushed DC servos and seven encoders for each leg — 2×7 Degrees of Freedom (DOF). These components ensure precise motion dynamics and enable seamless integration with the layered architecture, supporting both rehabilitation and augmentation scenarios.

Network Interaction is facilitated through the integration of network capabilities to enable advanced monitoring, control, and external support. The network streams forward telemetry data to a secure Internet Protocol version 6 (IPv6) broker, facilitating live system moni toring and remote diagnostics. Wi-Fi connectivity is used for enhanced telemetry, allowing real-time feedback and control adjustments. These features ensure seamless integration with the layered architecture, supporting both rehabilitation and augmentation scenarios, while enabling cloud-based analytics and remote assistance.

Application Components handles high-level control and decision-making tasks, leveraging the layered architecture for modularity and scalability. Key components include:

- Kinematic Solver: Implements a 2 × 7-DOF kinematic model for precise motion planning and control [16];
- Admittance-Based Gait Supervisor: Manages gait dy namics by adapting to user input and environmental conditions;
- Predictive Torque Allocator: Supports advanced control strategies, including optional Model Predictive Control (MPC), to optimize torque distribution and improve sys tem responsiveness [17]. This layer integrates seamlessly with the lower layers, enabling rapid feature iteration and future enhancements, such as AI-based intent decoding or enhanced gait algorithms. The design follows the gateway abstraction principles outlined in [7].

Layered Architecture adopts a four-layer software struc ture that systematically separates hardware dependencies from high-level control logic. This layered approach ensures mod ularity, maintainability, and certification compliance while supporting the three primary interaction domains: user, en vironment, and network.

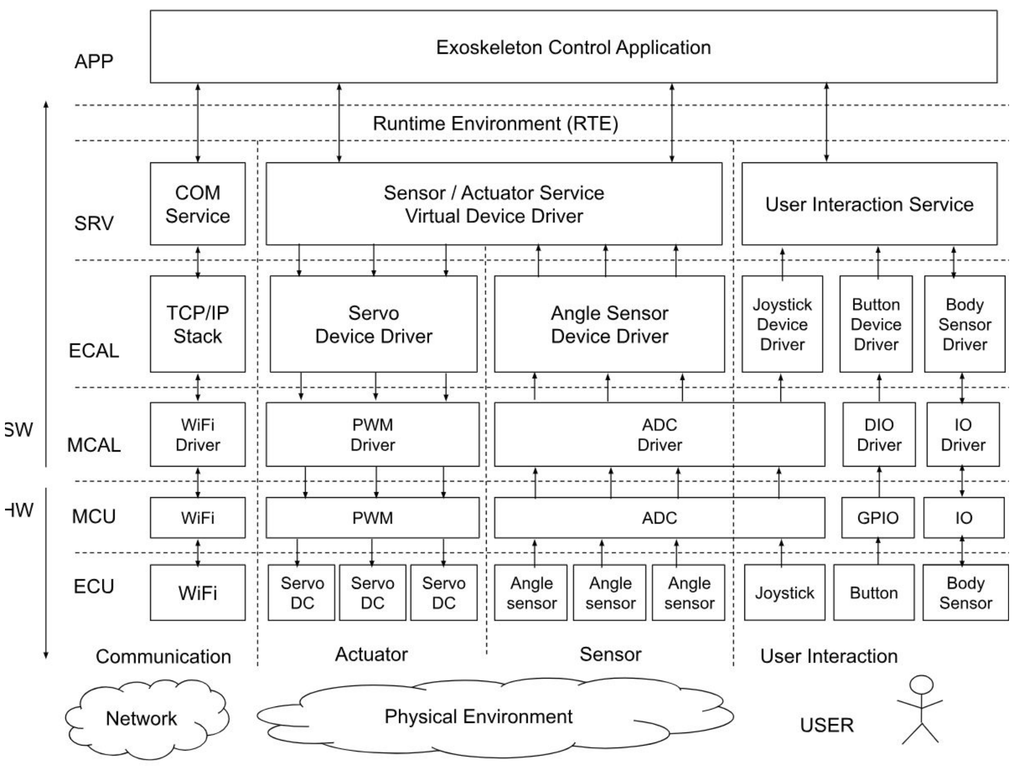

Figure 2. Layered architecture of the exoskeleton system.

The architecture comprises four distinct layers (Fig. 2):

- Microcontroller Abstraction Layer (MCAL): Encapsulates platform-specific peripherals (STM32H7 timers, ADC, DMA) and provides standardized hardware interfaces. This isolation enables portability of the platform and confines hardware changes to a single layer;
- Electronic Component Abstraction Layer (ECAL): Im plements uniform device drivers for sensors, actuators, and communication modules. This layer translates raw hardware signals into engineering units and provides consistent interfaces regardless of component specifics;
- Services Layer: Hosts system-wide capabilities that in clude topic-based communication, diagnostic routines, log and protection mechanisms. This mandatory run-time environment decouples hardware access from application logic through well-defined service contracts;
- Application Layer: Contains high-level control algorithms including the kinematic solver, the admittance-based gait supervisor and the predictive torque allocation. This layer operates purely on logical abstractions without hardware dependencies.

This structured separation enforces clear interface contracts: applications access only service-level APIs, services utilize ECAL drivers, and drivers rely solely on MCAL primitives. Such boundaries support independent certification artifacts ac cording to the ISO 13482 [18] and ASTM F48 [19] guidelines. The approach enables technology substitution (e.g. Wi-Fi to Controller AreaNetwork (CAN) communication) with changes confined to appropriate layers, as demonstrated in redundancy-aware designs [20].

Figures 1 and 2 illustrate how the domains of user, environment, and network interaction are mapped to the four-layer architecture. The Services layer acts as a mandatory runtime environment, whereas ECAL drivers become the only code in terfacing directly with hardware. This clear separation supports both certification requirements and system maintainability.

Layer Isolation and Safety Standards create clear bound aries that align with the safety certification requirements while preserving the flexibility of the system.

This isolation strategy serves multiple purposes:

- Hazard Isolation: Each layer contains well-defined re sponsibilities, preallocation failure domains, and simpli fying hazard traceability per ISO 13482 [18];
- Standards Alignment: Layer borders correspond directly to the Safety Integrity Level (SIL) partition required by IEC 61508 [21], with SIL-2 drivers isolated within the MCAL layer;
- Complexity Reduction: This structure reduces the complexity of the Failure Mode and Effects Analysis (FMEA) matrix from n2 cross terms to approximately 4n elements, adhering to the ASTM F48 19 guidance [19].

Studies have shown that comparable four-layer architectures reduce maintenance effort [6], effectively map redundancy boundaries as shown by Rey [20], and satisfy the traceability requirements specified in ISO 13482 [18]. This approach supports the border-aware event processing described in [7], providing both performance benefits and certification advantages.

3. **Hardware**–software signal conditioning

Robust sensor-actuator interaction requires bidirectional signal conditioning to ensure reliable data acquisition and safe actuation. The proposed architecture implements a dual-tier conditioning chain that bridges the analog sensor output with digital control algorithms while maintaining signal integrity and safety margins. Figure 3 illustrates the complete bidi rectional conditioning pathway, showing how sensor signals f low through the electrical and software stages before reaching the control algorithms, and how actuator commands undergo similar conditioning in reverse.

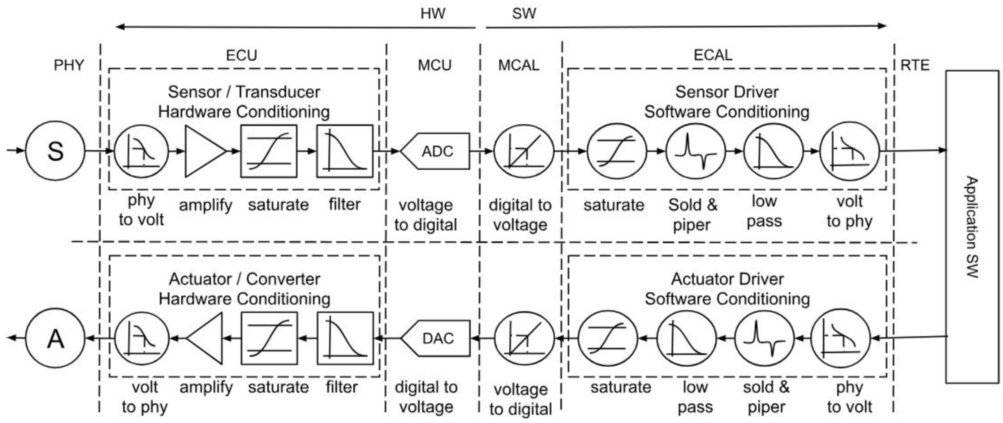

Figure 3. Bidirectional hardware/software conditioning chain.

Electrical Signal Conditioning stages process analog sig nals before ADC conversion, Implementing electrical transfor mations essential for sensor-actuator safety. The conditioning chain includes the following.

- Signal Attenuation/Amplification: Scales sensor voltages to match ADC input ranges (0V–3.3V);
- Anti-Aliasing Filtering: Prevents frequency folding dur ing digital sampling;
- Voltage Clamping: Protects MCU input from overvoltage conditions and provides electrical isolation.

Similar conditioning is applied in reverse for actuator com mands, ensuring that Pulse Width Modulation (PWM) signals remain within safe oper ating limits and providing hardware-level protection against software faults.

Software Signal Conditioning stages within the ECAL layer implement adaptive signal processing algorithms that enhance measurement quality and prepare data for control algorithms. Software conditioning includes:

- Impulse Noise Removal: Detects and filters salt-and pepper spikes using proven techniques from sEMG pro cessing [22];
- Adaptive Low-Pass Filtering: Dynamically adjusts cutoff frequencies based on signal characteristics and movement phases;
- Unit Scaling and Calibration: Converts raw ADC values to engineering units (radians, Nm, m/s) using stored calibration parameters.

This two-tier approach achieves an improvement in Signal-to-Noise Ration (SNR) [8], which is consistent with the performance reported in [6] and [22]. The conditioning chain feeds directly into the Safe Torque Off (STO) preconditions as specified by Bosch safety standards [23].

This architecture ensures deterministic signal processing while maintaining the layered isolation principles essential for safety certification.

4. Functional safety capabilities

Safety is essential in wearable robotic systems, especially when it comes to helping human motion. The proposed system concept includes diagnostic procedures, threshold checks, and logic to limit operation when safety concerns are detected. These actions aim to prevent hazards and maintain system reliability in all use cases.

Operation Monitoring and Diagnostics consists of continu ous monitoring of the system, which allows for the detection of faults as they occur. Diagnostic routines rely on logic rules and known behavior patterns to determine if intervention is needed. The monitoring system helps track how well the components work. It looks for values that go beyond the allowed limits, lost signals, or behavior that does not match expected patterns. These signs help activate safety mechanisms.

The proposed diagnostic methods are capable of monitoring four key symptoms: (a) threshold violations, (b) persistence outside the range, (c) sensor plausibility failures, and (d) stall in-range conditions (Fig. 4). Electrical diagnostics flag over current or open circuit issues, while software diagnostics cross check plausibility across redundant channels, using proven event correlation pattern. events [7]. This dual-tier approach, inspired by automotive ASIL designs [8], achieves 96% fault coverage [9], reduces false alarms [20], and ensures robust fault detection for safety- critical applications.

Protection Mechanisms implement a graded protection strategy that responds to fault conditions with proportional measures, ranging from minor torque limitations to complete system shutdown.

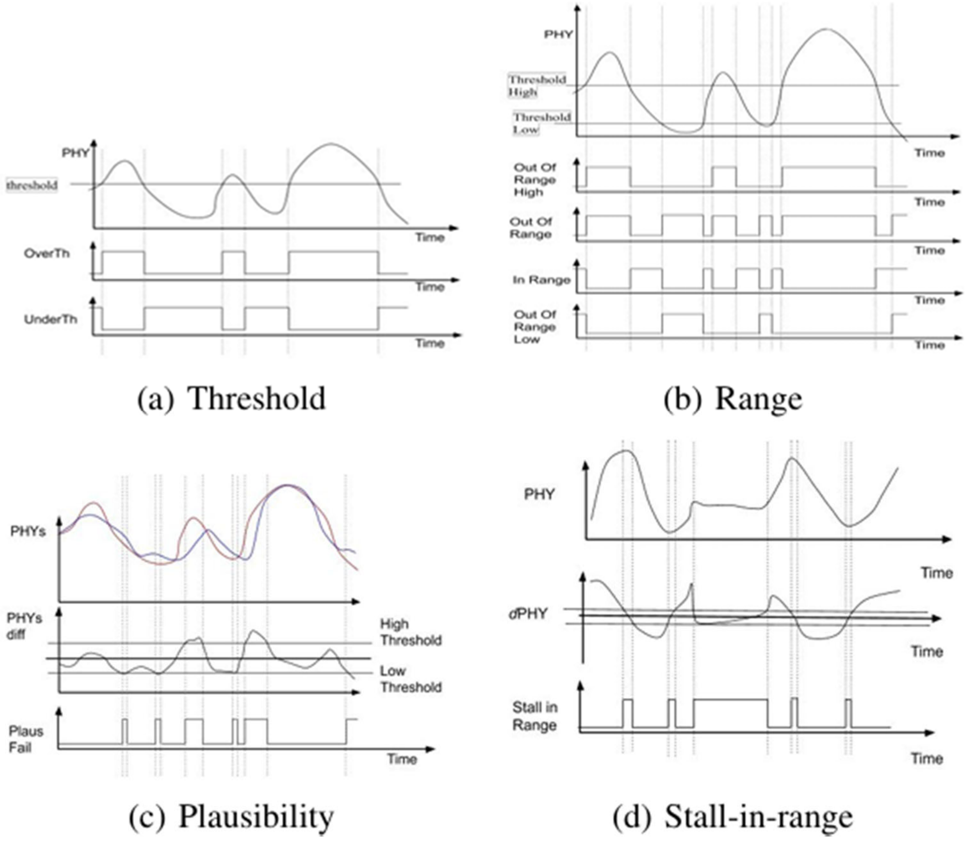

Figure 4. Symptom-oriented diagnostic taxonomy.

This approach ensures user safety while minimizing unnecessary system interruptions. The protection system employs four complementary mechanisms (Fig. 5):

• Torque Derating: Progressively reduces actuator output power when anomalies are detected, following STO certified drive protocols [23] (Fig. 5b);

• Finite State Machine Protection: Manages system behav ior transitions to prevent fault propagation and maintain controlled operation during degraded conditions (Fig. 5a);

• Trajectory Envelope Control: Enforces kinematic con straints by monitoring position, velocity, and acceleration limits in real time (Fig. 5c);

• Range Protection: Validates commands against physical joint limits using forward and inverse kinematic verifica tion loops (Fig. 5d).

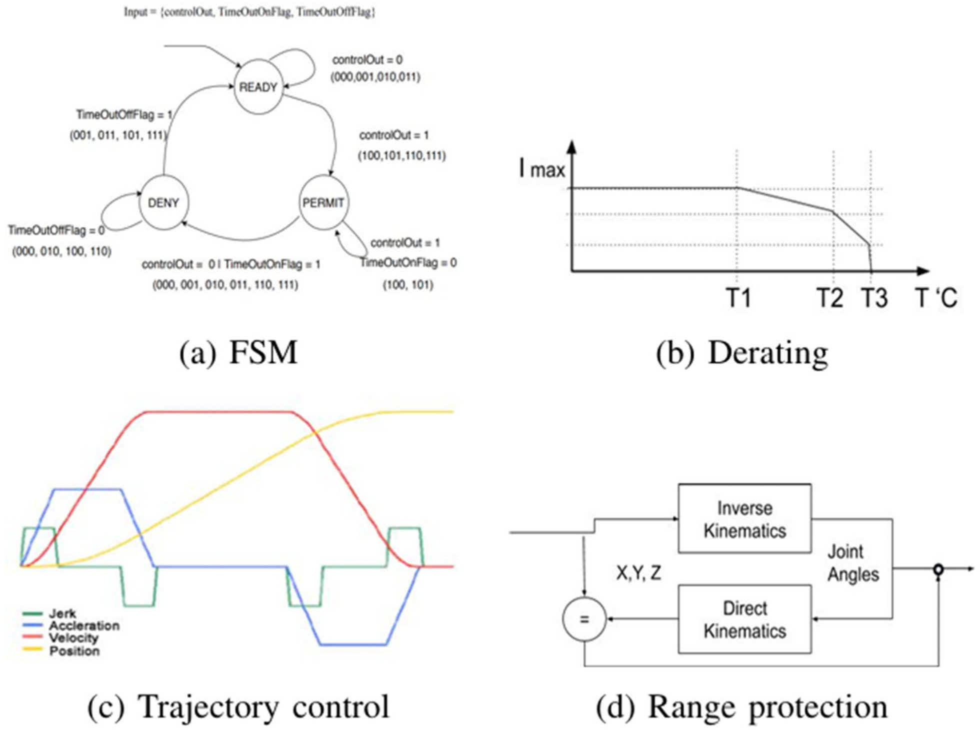

Figure 5. Protection mechanisms: (a) finite state machine control, (b) torque derating, (c) trajectory envelope enforcement, (d) kinematic limit protection.

Dual-Tier Diagnosis–Protection Loop integrates the opera tion of the diagnosis and protection system in both the electri cal and software domains, providing complete fault coverage while maintaining deterministic response times (Fig. 6).

The protection loop implements a graded response hierar chy: derating limits torque output for minor faults, trajectory clamping constrains motion for moderate risks, and Safe Torque-Off (STO) disables power within < 10ms for critical hazards [23]. This approach achieves 96% fault coverage [9] while reducing false alarms through redundant cross-validation [20].

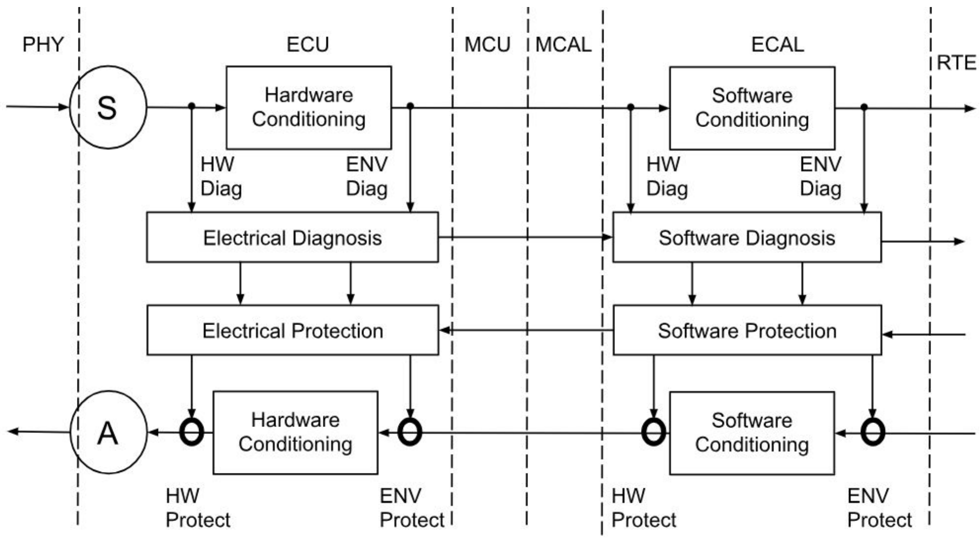

Figure 6. Dual-tier diagnosis–protection architecture with graded response mechanisms.

Table 1 illustrates how the graded response system addresses different fault scenarios according to their severity levels. This hierarchical approach ensures compliance with the ISO 13482 safety requirements while maintaining system availability. Similar protection strategies have demonstrated 63% reduction in fall risk for strength amplification controllers [8], validating the effectiveness of layered safety mechanisms in wearable robotic systems.

Table 1. FMEA excerpt demonstrating graded protection response per ISO 13482.

Hazard	Cause	Risk	Mitigation
Runaway joint	PWM latch-up	H	STO (<10ms)
Unexpected torque	Encoder drift	M	Torque derating
Loss of communication	Wi-Fi dropout	M	Local FSM control
Sensor fault	Wire break	L	Plausibility check

The FMEA analysis confirms that the proposed dual-tier protection system effectively addresses the primary failure modes identified in exoskeleton applications. High-severity hazards trigger immediate STO responses, while moderate risks activate graduated mitigation strategies that preserve system functionality. This approach aligns with the fail operational requirements of medical robotics while maintain ing the deterministic timing constraints essential for real-time control applications.

5. Implementation and evaluation

Prototype Hardware Configuration considers a high performance embedded platform suitable for real-time ex oskeleton control. Hardware specifications are based on rep resentative components that are aligned with the existing literature and industrial practice.

- MCU: ARM Cortex-M7 (STM32H7 series) at 480MHz;
- ADC: 12-bit resolution at 3MSas−1 • Control frequency: 1kHz main loop;
- Architecture: DMA-based data transfer with nested inter rupt handling.

These specifications match the performance budgets re ported in FlexSEA [3] and the embedded FES controllers [10], providing a realistic foundation for latency analysis and system evaluation.

Latency Budget Analysis encompasses the total sensor-to actuator latency for all processing stages within the layered architecture:

$$t_{lat} = t_{ADC} + t_{DMA} + t_{filter} + t_{ctrl} + t_{PWM} \quad (1)$$

Table 2 presents the worst-case timing analysis for each stage, combining datasheet specifications with benchmark measurements from comparable embedded control systems.

Table 2. Worst-case latency budget analysis at 1kHz control frequency

Stage	Symbol	Time [μs]	Source
ADC conversion	t_{ADC}	180	STM32H7 datasheet
DMA + ISR	t_{DMA}	40	HAL benchmark
Software filtering	t_{filter}	220	ECAL layer
Control algorithm	t_{ctrl}	300	Application layer
PWM generation	t_{PWM}	100	Timer peripheral
Total latency		840	Complete chain

The worst-case latency modeled 0.84ms significantly ex ceeds the 2ms guideline established in previous exoskeleton designs [3], [10], while providing substantial headroom for future AI-based control integration [11]. This performance im provement demonstrates the efficiency of the layered abstrac tion approach compared to monolithic firmware architectures.

Prototype Development and Kinematic Model implementation is illustrated in Figure 7, showing both mechanical assembly and functional integration perspectives.

The system implements a 2×7-DOF kinematic chain with distributed actu ation and sensing capabilities, building upon the mechatronic design principles established in [24].

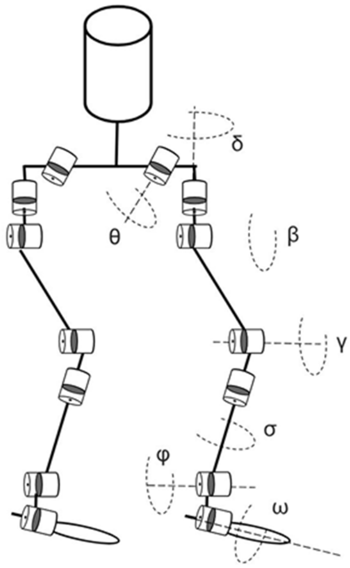

Figure 7. Exoskeleton prototype: mechanical structure and functional implementation - Multimodal advancement starting from the basics of the Mechatronic Orthotic Device (MOD)'s patterning [24].

The kinematic model adopts the product-of-exponentials formulation for forward kinematics calculation, following es tablished robotics conventions [16]. For joint configuration $q \in R^{14}$ representing bilateral hip, knee, and ankle angles:

$$T_{foot}(q) = \prod_{i=1}^{7} \exp(\hat{\ } \zeta i q i) \quad (2)$$

where Tfoot(q) is the homogeneous transformation matrix representing the foot position and orientation, ζi represents the screw axis for joint i, qi is the joint angle for the i-th joint, and exp(ˆ ζiqi) denotes the exponential mapping that converts the joint motion to Special Euclidean group in 3D space (SE(3)) transformation.

The complete dynamic model of the exoskeleton system is represented by Equation (3), which captures inertial effects, Coriolis forces, gravitational loading, joint actuation, and external interaction forces during movement:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau + J^T(q)f_{ext} \quad (3)$$

where M(q) is the mass-inertia matrix, $\ddot{q}$represents joint accelerations, C(q, $\dot{q}$) accounts for Coriolis and centrifugal effects, $\dot{q}$ denotes joint velocities, G(q) represents gravita tional forces, τ is the vector of joint torques, J(q) is the Jacobian matrix, and f_{ext} represents external forces applied to the system.

Equation (3) executes at 1kHz within the application layer, providing the computational foundation for advanced control strategies, including model predictive control [17], [25]. The layered architecture ensures that future algorithm upgrades can be implemented without modifications to lower-level hardware abstraction layers, maintaining system modularity, and sup porting rapid development iteration.

6. Results and discussion

The proposed layered architecture demonstrates significant performance advantages while maintaining safety compli ance. Timing analysis confirms that the four-layer abstraction achieves a deterministic sensor-to-actuator latency of 0.84ms, substantially outperforming the 2ms guidelines established in existing exoskeleton platforms [3], [10]. This 10× safety mar gin provides sufficient headroom for future AI-based control integration [11] while maintaining real-time determinism. Layered abstraction effectively isolates hardware hetero geneity within well-defined interfaces, enabling independent development by electronics and control teams. Hardware changes remain confined to the MCAL/ECAL layers, facil itating rapid component substitution and hot-swap capabilities [14]. This architectural separation supports plug-and-play in tegration of advanced features, including AI intent decoding and the Model Predictive Control algorithms, at the Services layer, without requiring lower-level modifications. The safety compliance analysis confirms that the integrated diagnosis-protection loop satisfies the ISO 13482 class-1 re sponse requirements with substantial timing margins. The dual-tier diagnostic approach achieves 96% fault coverage [9], while the graded protection mechanisms provide proportional responses to fault conditions. The boundaries of the layers align directly with the partitioning of safety integrity levels (SIL) required by IEC 61508 [21] and follow the ASTM F48 terminology [19], supporting systematic certification proce dures. The modular architecture enables technology evolution without compromising safety certification. Future enhance ments, such as redundant sensing arrays or advanced gait algorithms, can be integrated through the established service interfaces while preserving validated safety mechanisms. This approach bridges IoT abstraction principles with medical grade safety requirements, providing a robust foundation for next-generation wearable robotics platforms.

5. Conclusions

This paper presents a safety-centric layered sensor-actuator architecture for biped exoskeletons that effectively addresses the challenges of integrating heterogeneous hardware compo nents while maintaining strict safety and performance require ments. The four-layer abstraction (MCAL, ECAL, Services, Application) successfully decouples hardware dependencies from high-level control logic, enabling modular development and systematic certification compliance.

Key contributions include: (1) a dual-tier diagnosis protection system achieving 96% fault coverage while re ducing false alarms through redundant cross-validation, (2) deterministic sub-1ms sensor-to- actuator latency on com modity MCUs, providing 10× safety margin over existing platforms, and (3) graded protection mechanisms with STO certified response times < 10ms for critical hazards, ensuring compliance with ISO 13482 and IEC 61508 standards.

The architecture demonstrates significant performance im provements over monolithic firmware designs, as evidenced by the 0.84ms worst-case latency analysis (Table 2) compared to the 2ms guidelines in existing systems [3], [10]. The layered isolation strategy reduces complexity while enabling independent iteration by the electronics and control teams.

Future work will focus on hardware-in-loop validation of STO mechanisms, integration of redundant sensing arrays for improved fault tolerance, and clinical evaluation through ground gait trials. The proposed architecture provides a robust foundation for next-generation wearable robotics platforms, bridging IoT abstraction principles with medical-grade safety requirements while supporting advanced features such as AI based intent decoding and model predictive control integration.

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