Ensuring Stability in Power-Loss Scenarios: A Safety Framework for Humanoid Robots

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***Abstract*—This study aims to develop a detailed safety system for humanoid robots with an emphasis on maintaining stability and operational security during unexpected power outages. The approach combines experimental and computational techniques to create and assess various mechanisms, including passive stabilization methods, fail-safe control systems, and supplementary power sources. The findings indicate that integrating these mechanisms substantially improves the robot's ability to withstand power interruptions, thereby maintaining stability and the ongoing operation of critical functions during key moments. Additionally, the research examines the relevance of specific standards such as ISO 10218 and ISO/TS 15066 to ensure that the robot safety measures conform to recognized safety norms. In summary, the results support the implementation of a comprehensive safety framework that merges sophisticated mechanical configurations, control tactics, and power management systems. These elements are essential for enhancing the dependability and safety of humanoid robots in settings where they interact with humans. This study highlights the significance of adhering to standards and adopting innovative safety features to propel robotic technology forward in unpredictable operational environments.**

***Index Terms*—Humanoid Robots, Power-Loss Scenarios, Safety Protocols, Robotic Stability, Emergency Energy Reserves, Adaptive Control Systems ISO 26262, ISO 10218, ISO/TS 15066, DO-178C, Technological Adaptation**

I. Introduction

HUMANOID robotics represents a significant stride towards replicating human actions and forms, paving the way for versatile applications in modern robotics. As these robots evolve through artificial intelligence and breakthroughs in sensory advancements, their operational domains extend beyond predefined settings to include unpredictable environments. Nonetheless, their operational stability and safety are a pivotal concern during unexpected power failures. This paper delineates a comprehensive safety protocol designed explicitly for humanoid robots, prioritizing stability to meet the challenges of dynamic and human-centric environments.

A. *Contextual Overview of Humanoid Robots Across Diverse Settings*

Humanoid robots find utility in an expansive range of environments, from highly controlled industrial areas to the unpredictability of unstructured landscapes. Their anthropomorphic structure is ideal for navigating environments crafted for humans, thus making them essential in disaster recovery, elderly care, and cooperative manufacturing. Here are a few scenarios:

- Industrial Applications: Humanoid robots are critical to boosting productivity in industrial settings. They execute repetitive or dangerous tasks, enhancing safety and operational efficiency [1].
- Navigating Unstructured Environments: They employ sophisticated locomotion technologies, such as neural oscillators, to traverse uneven and dynamic terrains, effectively adjusting to varying environmental conditions [2].
- Human-Robot Interactions (HRI): Maintaining stability and safety is crucial in environments where humans and robots work closely. Established safety frameworks ensure humanoid robots remain passive and stable during physical interactions, thus preventing any incidents of instability [3].
- Emergency and Disaster Response: Equipped with advanced stability control systems, humanoid robots can maneuver through debris and challenging terrains during emergency response efforts, showcasing their robustness in the face of disturbances [4].

The diverse applications of humanoid robots underline the importance of sophisticated control and safety mechanisms capable of effectively managing varying environmental conditions. Innovations in their control systems, such as the integration of energy-efficient actuators and adaptive admission control, are expected to improve the safety and efficacy of these robotic systems [5].

These developments expand the operational capabilities of humanoid robots and emphasize the critical need for specialized safety protocols that guarantee their reliability and stability in multifarious scenarios.

B. *Challenges Stemming from Sudden Power Disruptions in Humanoid Robots*

Humanoid robots are engineered to replicate human-like movements involving intricate balancing and coordination across multiple joints. A sudden cessation of power presents several challenges that can affect the stability, operational capabilities, and safety of the robot. Here are some critical issues:

- Loss of Control Over Actuators: An abrupt power outage can cause immediate cessation of motor functions essen-

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tial for joint articulation and balance maintenance. This loss of control can result in the robot falling, which risks damaging the robot itself and poses a safety hazard to humans in proximity [1].

- Compromised Balance and Stability: Humanoid robots usually rely on real-time control systems that adjust their center of mass in relation to their base of support to maintain balance. Power interruptions can disrupt these systems, leading to instability and potential falls, particularly problematic in uneven terrains or during swift movements [2].
- Increased Risks in Dynamic Settings: The challenges are exacerbated in dynamic environments, such as disaster sites or crowded spaces, where a power loss could lead to uncontrolled robot movements that might injure people or damage objects in the vicinity [4].
- Data and Operational Recovery Issues: Interruptions in the power supply can result in the loss of critical sensor data and incomplete processing operations, complicating the resumption of tasks, especially in collaborative or precision-dependent activities [5].
- Delays in Emergency Procedures: In urgent situations like search and rescue operations, delays caused by power outages can hinder immediate emergency responses, such as moving to a safe posture or signaling for help [6].
- Challenges in Energy Management: Complex humanoid robots with sophisticated electro-hydraulic systems face significant challenges in managing residual energy when power is lost, potentially leading to further instability or mechanical damage [7].

The array of challenges posed by sudden power disruptions underscores the essential need for effective safety protocols and emergency response strategies. Implementing passive stability enhancements, energy-conscious actuators, and fail-safe mechanisms can mitigate risks related to falls, equipment damage, and delays, ensuring reliability and safety under adverse conditions.

C. The Critical Role of Safety and Stability in Power Interruptions

Ensuring safety and stability during power interruptions is paramount for humanoid robots, especially as their applications increasingly intersect with human activities, hazardous environments, and high-stakes operations. The reasons for prioritizing safety and stability include:

- Protection Against Human Injury and Environmental Damage: In collaborative environments, such as those found in elder care, rehabilitation, or industrial manufacturing, the abrupt failure of a humanoid robot could inflict physical harm on humans and cause environmental damage. Maintaining stability during power failures minimizes these risks, enhancing the trust and dependability of human-robot interactions [5].
- Maintenance of Robotic Integrity: Humanoid robots represent substantial investments with complex hardware and software integrations. Falls or uncontrollable shutdowns can necessitate costly repairs or total system failures. Stability measures protect the robot's structural integrity, reducing maintenance costs and operational downtime [2].
- Support for Essential Functions: Power failures can compromise the robot's ability to perform essential tasks in critical applications such as disaster recovery or medical aid. Safety mechanisms ensure robots can enter safe states and maintain their functionality for quick recovery or intervention [4].
- Assurance of Operational Continuity: Safety and stability systems enable humanoid robots to effectively manage unexpected power outages by utilizing passive systems or managing residual energy. This capability is crucial for maintaining continuity, particularly when interruptions can trigger broader impacts, like industrial facilities or public areas [7].
- Risk Mitigation in Dynamic Settings: Stability becomes even more critical in dynamic and potentially hazardous settings, such as construction sites or crowded venues. A destabilized robot can increase the risk of accidents, underlining the importance of robust stability mechanisms to prevent mishaps and comply with safety norms [6].

In scenarios where power loss is possible, integrating sophisticated safety and stability systems is indispensable. These systems protect humans, ensure the integrity of the robot, and facilitate the continuation of vital operations, allowing humanoid robots to function efficiently across a wide spectrum of challenging and variable environments.

D. Paper Structure

The Introduction outlines the significance of developing robust safety protocols for humanoid robots, focusing on scenarios involving unexpected power losses. It emphasizes integrating passive stabilization methods, fail-safe control systems, and supplementary power sources to enhance the robot's operational security and stability.

Section II: Review of Pertinent Standards analyzes critical safety standards such as ISO 10218 and ISO/TS 15066. This section evaluates how these standards contribute to safety in robotic operations and identifies gaps where current standards may not fully address the challenges posed by power interruptions.

Section III: Risk Evaluation and Safety Imperatives focuses on assessing the risks associated with power disruptions and discusses comprehensive mitigation strategies. This section argues for the development of robust risk assessment frameworks and sturdy emergency response systems specifically designed to handle power-related contingencies.

Section IV: Stability and Safety in Humanoid Robots explores mechanical and control strategies for maintaining stability and safety during power losses. It discusses passive stabilization techniques and the integration of redundant power systems and emergency energy reserves.

Section V: Safety Integration Protocols synthesizes the approaches discussed throughout the paper into a cohesive framework, outlining how various safety protocols can be integrated to enhance the operational security of humanoid robots.

Section VI: Discussion critically examines the implications of the findings and compares them with existing literature, providing a nuanced discussion on the practicality and limitations of the proposed safety measures.

Section VII: Future Work suggests directions for future research, emphasizing areas where further technological innovations and standard developments are needed to address the evolving safety challenges in humanoid robotics.

Section VIII: Conclusion summarizes the paper's key findings, reiterating the importance of advanced safety frameworks for humanoid robots. It highlights the need for ongoing improvements in safety technologies to adapt to the dynamic operational environments where these robots are deployed.

This approach allows the article to comprehensively address the complexities of ensuring safety and stability in humanoid robots, providing a clear roadmap for ongoing and future research initiatives.

II. Review of Pertinent Standards

A. Analysis of ISO 10218 and ISO/TS 15066: Emphasis on Safety Protocols and Emergency Measures in Robotics

1) ISO 10218: Protocols for Industrial Robot Safety ISO 10218 stands as a foundational standard in industrial robotics, aimed at securing safe interactions between robots and human operators within shared operational areas. This regulation mandates precise criteria for designing, producing, and assimilating robotic systems to mitigate hazards. Additionally, it encompasses provisions for control systems that incorporate safety-rated operational features and collaborative functionalities. Significant aspects include:

- The implementation of protocols for safety-rated monitored stops and power constraints to regulate force during user interactions [8].
- Adapted risk evaluation techniques for various robotic applications [9].
- ISO 10218 has been pivotal in facilitating cooperative environments by introducing operational protocols for Speed and Separation Monitoring (SSM) and establishing contact force limits. Despite its contributions, the standard faces challenges in addressing the dynamic aspects of human-robot interactions [10].

2) ISO/TS 15066: Safeguarding Human-Robot Collaboration Expanding on ISO 10218, ISO/TS 15066 specifically targets the safety of collaborative robots (co-bots) that directly interact with human operatives. It delineates comprehensive criteria for acceptable force and pressure during these interactions to ensure safety during cooperative tasks. Principal elements include:

- Defined limits for the maximum permissible forces and pressures during direct physical contact with humans [11].
- Risk evaluation approaches and techniques for the safe design of collaborative work environments [9].

This specification is dedicated to implementing practical safety measures, such as restrictions on robot velocities and forces in proximity to humans. It incorporates thorough safety protocols for physical human-robot collaboration, with a focus on hazard analysis and risk mitigation [9].

3) Challenges and Prospective Developments : While ISO 10218 and ISO/TS 15066 provide a substantial framework for robot safety, their application poses significant challenges in dynamic or high variability environments. Continuous research efforts are directed towards enhancing these standards to better suit practical applications and elevate safety standards across diverse robotic scenarios [12].

Together, these standards form a comprehensive blueprint for ensuring safety and emergency responses in industrial and collaborative robotics, enhancing both the functionality and security of human-robot interactions.

B. ISO 13482: Safeguarding Interactions in Personal Care Robotics

1) Examination of ISO 13482 : ISO 13482:2014 emerges as a pivotal standard tailored for personal care robots, focusing primarily on safety in their operation near humans. This norm sets forth comprehensive protocols to ensure that robots engaged in personal care tasks—such as aiding the elderly or individuals with disabilities—perform securely, especially during direct interactions. Essential components of ISO 13482 comprise methodologies for risk evaluation, stipulations for safety requirements, and preventive strategies to mitigate risks during human-robot exchanges [13].

2) Principal Characteristics of ISO 13482:

- Purpose and Reach: This standard is tailored for personal care robots, including mobile servant robots, physical assistance robots, and personal transporters [14].
- Risk Evaluation and Hazard Analysis: ISO 13482 advocates for an exhaustive risk assessment framework, scrutinizing potential hazards arising from physical interactions between humans and robots. The standard underscores the necessity of functional safety measures in robot design to avoid injuries during standard operations [15].
- Interactions with Humans: Diverging from standards applicable to industrial robots like ISO 10218, ISO 13482 concentrates on safety within non-industrial settings where robots and humans interact closely. It mandates stringent controls over the physical forces robots can exert to minimize injury risks [16].
- Design and Production: The standard promotes the creation of robots with built-in safety features, such as rounded contours and compliance mechanisms. It also emphasizes the importance of implementing control systems that include emergency stops and fault detection capabilities [17].

3) Challenges and Constraints :

- Vagueness in Directives: The standard offers a conceptual framework that lacks precise quantitative criteria for specific safety measures, which complicates compliance and validation for developers [13].
- Suitability for Public Settings: Although the guidelines are designed predominantly for private contexts like homes or healthcare facilities, they fail to address the

complexities encountered in public spaces, where unpredictable interactions and dense crowds pose additional challenges [18].

ISO 13482 sets a fundamental standard for safeguarding human-robot interactions within personal care contexts. While it lays down a solid basis for risk assessment, functional safety, and human-focused design principles for the safe development of personal care robots, enhancements are necessary to extend its applicability across more varied environments.

C. Implementation of DO-178C and DO-254: Ensuring Dependability in Critical Systems

1) Overview of DO-178C and DO-254 : DO-178C, titled "Software Considerations in Airborne Systems and Equipment Certification," is a crucial norm in the aviation sector for assuring the dependability and safety of software used in airborne systems. Concurrently, DO-254, known as "Design Assurance Guidance for Airborne Electronic Hardware," prescribes the protocols for developing and certifying electronic hardware components. Collectively, these standards stipulate meticulous procedures to verify that critical systems adhere to rigorous safety and reliability standards.

2) Principal Elements of DO-178C:

- Software Development Lifecycle: DO-178C prescribes a comprehensive software development lifecycle encompassing stages such as planning, requirement specification, design, implementation, verification, and configuration management. This model is designed to ensure meticulous traceability and the systematic elimination of errors throughout the development process [19].
- Verification and Validation: This standard underlines the importance of stringent verification techniques, such as requirements-based testing, to uncover and rectify software faults that could compromise safety [20].
- Model-Based Development: Enhancements in DO-178C include supplementary provisions like DO-331, which advocate model-based development approaches. These methods improve efficiency and facilitate precise tracing of requirements [21].
- Error Prevention and Fault Tolerance: Focus is given to preemptive error prevention through the early identification and rectification of faults, along with implementing strategies for fault tolerance to manage unforeseen failures [22].

3) Principal Elements of DO-254:

- Hardware Design Assurance: DO-254 categorizes hardware components into different assurance levels (DALs), dictating the rigor of processes and verification activities according to the potential risk associated with a failure [23].
- Tool Qualification: The standard mandates the qualification of hardware design tools to prevent them from introducing errors and thus ensure the reliability of the design and manufacturing stages [24].
- Hardware Validation: It emphasizes the necessity of validation methods such as failure mode analysis and environmental testing to affirm that hardware fulfills the required safety and performance standards [25].

4) Challenges and Prospects :

- System Integration Challenges: To guarantee overall system reliability, the effective implementation of DO-178C and DO-254 necessitates a seamless integration of hardware and software development efforts [25](Basagiannis, 2016).
- Legacy Systems: The certification of older systems under these standards presents distinct challenges, such as conforming to contemporary regulatory demands and incorporating advanced verification techniques [26].
- Cost and Efficiency: Initiatives aimed at optimizing certification procedures, like adopting model-driven engineering, seek to reduce both time and costs while upholding stringent reliability standards [27].

DO-178C and DO-254 establish a comprehensive framework crucial for software and hardware reliability and safety in critical systems, especially in high-stakes fields like aerospace. These standards are fundamental in structuring development processes, enforcing thorough validations, and facilitating integrated system reliability.

D. Deficiencies in Existing Standards for Power Loss Scenarios

Humanoid Robots Humanoid robots functioning in critical environments encounter numerous obstacles concerning power loss, which current standards fail to address comprehensively. This section delineates the observed gaps in these standards and their consequences.

1) Incomplete Guidelines for Power-Loss Events in Collaborative Robots :

- Concern: Prevailing standards like ISO/TS 15066 and ISO 10218 predominantly concentrate on operational safety and force thresholds, yet they neglect detailed provisions for handling power-loss situations in humanoid robots.
- Illustration: Haddadin et al. critique that existing safety models do not adequately account for real-time power disruptions, resulting in either overly cautious or inadequately prepared safety measures [12].

2) Inadequacies in Addressing Power Outages During Human-Robot Interactions :

- Issue: The current frameworks are insufficient in outlining appropriate robotic behaviors during power failures, especially in settings where human collaboration is involved and abrupt halts might pose risks to human safety.
- Example: Investigations into Power and Force-Limiting (PFL) technologies reveal that while they are engineered for collision safety, they fail to consider the robot's dynamic reactions in power outage scenarios [28].

3) Scarcity of Provisions for Energy Backup and Storage Solutions :

- Challenge: There is a notable absence of standards promoting effective energy backup systems that could maintain stability amidst power disruptions.

TABLE I: Comparison of Standards in Humanoid Robot Safety During Power Losses

Standards	Focus on Humanoid Robots	Power Loss Provisions	Safety Features During Power Loss	Applicability to Humanoid Robots
ISO 10218	Industrial robot safety	No specific guidelines for power-loss scenarios	Safety-rated monitored stops	Primarily for industrial applications
ISO/TS 15066	Collaborative robots	Lacks detailed power-loss handling provisions	Power and force-limiting (PFL) technologies	Specific to collaborative settings
ISO 13482	Personal care robots	Minimal details on power-loss management	Emergency stop mechanisms	Suited for non-industrial applications
DO-178C	Software reliability	Detailed software response to failures	Emphasis on software fault tolerance	Indirect application via software systems
DO-254	Hardware reliability	Details on hardware behavior during interruptions	Focus on fault-tolerant hardware design	Indirect application via hardware systems

- Case Study: The work of Moradewicz and Kazmierkowski on contactless power supply systems demonstrates potential strategies for alleviating abrupt power cut-offs through alternative energy delivery methods [29].

4) Overlooking Environmental and Operational Dynamics :

- Observation: Existing standards often overlook the impact of environmental conditions, such as irregular terrain or mechanical stress during power failures, which can intensify safety hazards.
- Instance: Research by Lin and Berenson concerning humanoid navigation underscores the critical need for power stability in scenarios demanding precise navigational adjustments [30].

5) Limited Directions for Dynamic Response Capabilities :

- Shortfall: Current standards do not provide sufficient guidance concerning the incorporation of dynamic response systems that could counteract the impacts of power losses.
- Insight: Studies into adaptive collision sensitivity and dynamic control adjustments propose that integrating real-time sensing with motor management could significantly bolster safety during power interruptions [28].

Table I provides a detailed comparison of how each standard addresses—or fails to address—the specific challenges of maintaining stability in humanoid robots during power interruptions.

The prevalent standards significantly lack a comprehensive approach to addressing the complexities of power loss situations in humanoid robots. Comprehensive guidelines that encapsulate effective power management strategies, adaptive response systems, and reliable fail-safe protocols are imperative to ensure continued operational stability and safety during power interruptions.

III. Risk Evaluation and Safety Imperatives

A. Hazards Linked to Power Disruptions in Humanoid Robots

Interruptions in the power supply to humanoid robots can manifest several risks, such as involuntary movements, instability, or an absence of responsiveness to external controls, endangering both the robots and their operational surroundings. The following are synthesized insights from various scholarly works:

- Potential for Involuntary Movements: Loss of power might render actuators dysfunctional, precipitating unpredictable or abrupt motions. Such behaviors threaten human operators, particularly in settings where robots function alongside humans without physical barriers [31].
- Risks of Instability and Material Harm: When robots face power deficiencies, their equilibrium mechanisms may malfunction, potentially leading to falls. These incidents could damage the robot, cause injuries to nearby humans, or lead to destruction of property [11].
- Inefficacy in Emergencies: During critical interventions, a power failure could impair a robot's operational capabilities, including its ability to self-assess and rectify malfunctions, thereby exposing humans to potential dangers [14].
- Complications in Human-Robot Interaction: Interruptions due to power failures may disrupt collaborative operations, increasing the chances of accidents or mechanical breakdowns, thus highlighting the necessity for thorough risk evaluations to prevent such occurrences [32].
- Propensity for Comprehensive System Failures: Power interruptions may also cause safety features, such as braking systems or backup power supplies, to remain inactive, possibly leading to progressive malfunctions that heighten risks [33].
- Environmental Dangers: Robots deployed in harsh environments, such as in disaster relief or industrial operations, might intensify the repercussions of power failures, raising concerns about fire risks or chemical exposure [34].
- Challenges in Mitigating Risks: While existing standards like ISO/TS 15066 offer directives for safety in collaborative contexts, they require further enhancement to specifically address scenarios involving power disruptions [35].

To effectively manage the hazards of power loss in humanoid robots, it is essential to develop comprehensive risk assessment frameworks, implement sturdy emergency response systems, and comply with safety standards that specifically cater to power-related contingencies. Incorporating real-time diagnostic tools, redundant functionalities, and predictive maintenance strategies could significantly reduce these risks.

B. Comprehensive Risk Assessment Approaches Derived from ARP4761 and ISO 26262

Adapting risk assessment techniques from the aviation and automotive sectors, specifically ARP4761 and ISO 26262, greatly enhances safety measures in humanoid robots. Figure 1 illustrates the adapted risk assessment process, integrating ARP4761 and ISO 26262 methodologies to identify and mitigate hazards specific to power interruptions in humanoid robots.

1) Exploration of ARP4761 and ISO 26262 Standards:

- ARP4761 offers safety assessment methodologies for civil aviation systems, highlighting essential procedures such as Fault Tree Analysis (FTA), Failure Mode and Effects Analysis (FMEA), and Functional Hazard Assessment (FHA). It facilitates thorough risk evaluation during both the design and operational phases.
- ISO 26262 serves as a functional safety norm for automotive electronics, outlining a detailed method for Hazard Analysis and Risk Assessment (HARA). It emphasizes the assessment of risks, determination of hazard severity, and stipulating Automotive Safety Integrity Levels (ASIL).

2) Integration of ARP4761 into Humanoid Robot Safety:

- Functional Hazard Assessment (FHA):
  - This approach pinpoints hazards specific to humanoid robots, such as destabilization or erratic actions following a power disruption.
  - Systems are modeled using tools like the Architecture Analysis and Design Language (AADL) to predict and simulate potential failures [36].
- Fault Tree Analysis (FTA):
  - FTA methodically deconstructs potential hazard causes like power system failures or actuator defects into their fundamental elements.
  - It facilitates the examination of failure likelihoods and the relationships within the system's architecture [36].

3) Application of ISO 26262 to Humanoid Robots:

- Hazard Analysis and Risk Assessment (HARA):
  - HARA systematically evaluates risks by assessing Severity (S), Exposure (E), and Controllability (C), which helps in assigning appropriate ASIL.
  - Techniques like Simulation Aided Hazard Analysis (SAHARA) are employed to automate hazard assessment and minimize reliance on manual expert analysis [37].
- Failure Mode and Effects Analysis (FMEA):
  - This analysis identifies and evaluates potential failure modes within robot components such as sensors and motors and their impact on safety.
  - Integrating FMEA with the Proportional Risk Assessment Technique (PRAT) enhances the prioritization of risks quantitatively [38].
- Dynamic Risk Assessment:
  - o This technique incorporates continuous risk evaluation during operation, increasing adaptability to scenarios like power loss and augmenting overall system robustness [39].
- Risk Mitigation Framework:
  - A synergistic approach combines ARP4761's initial system-level evaluations with ISO 26262's detailed component-level hazard analysis and control.
  - It involves the creation of a Fault Injection framework to examine failure modes' diagnostic coverage and evaluate the effectiveness of mitigation tactics [40].
- Simulation-Based Analysis:
  - Advanced simulation tools offer deep insights into the mechanisms of failures, facilitating the prediction and validation of safety measures [41].

By leveraging the structured approaches of ARP4761 and ISO 26262, humanoid robots can significantly improve risk assessment and mitigation strategies, especially in managing power loss incidents. These methodologies provide a framework for systematic hazard identification, risk evaluation, and control, ensuring functional and operational safety.

C. Formulating Safety Protocols to Mitigate Identified Risks

Developing robust safety protocols to manage the hazards associated with power interruptions in humanoid robots is essential for maintaining system integrity and operational continuity. The following sections delineate the safety protocols derived from prevailing methodologies and scholarly research:

1) Redundancy in Power Supplies:

- Protocol: Introduce auxiliary power systems to guarantee continuous functionality during primary power disruptions.
- Rationale: Additional power sources bolster system resilience, averting abrupt terminations of robot operations that could lead to mechanical instability or erratic behaviors [42].
- Illustration: Employment of dual-mode computing systems featuring active and standby configurations to facilitate uninterrupted performance.

2) Adaptive Fault Tolerance:

- Protocol: Establish adaptive fault-tolerance mechanisms that recalibrate based on the severity of the task and prevailing power conditions.
- Rationale: Such adaptive mechanisms prudently manage power consumption while ensuring operational safety amid power variability [43].

3) Resilience in Mechanical Joints:

- Protocol: Construct joints capable of cushioning impacts during power losses, thus mitigating abrupt malfunctions or structural compromises.
- Rationale: Designing joints that absorb shocks reduces the likelihood of mechanical breakdowns during unforeseen power outages [44].

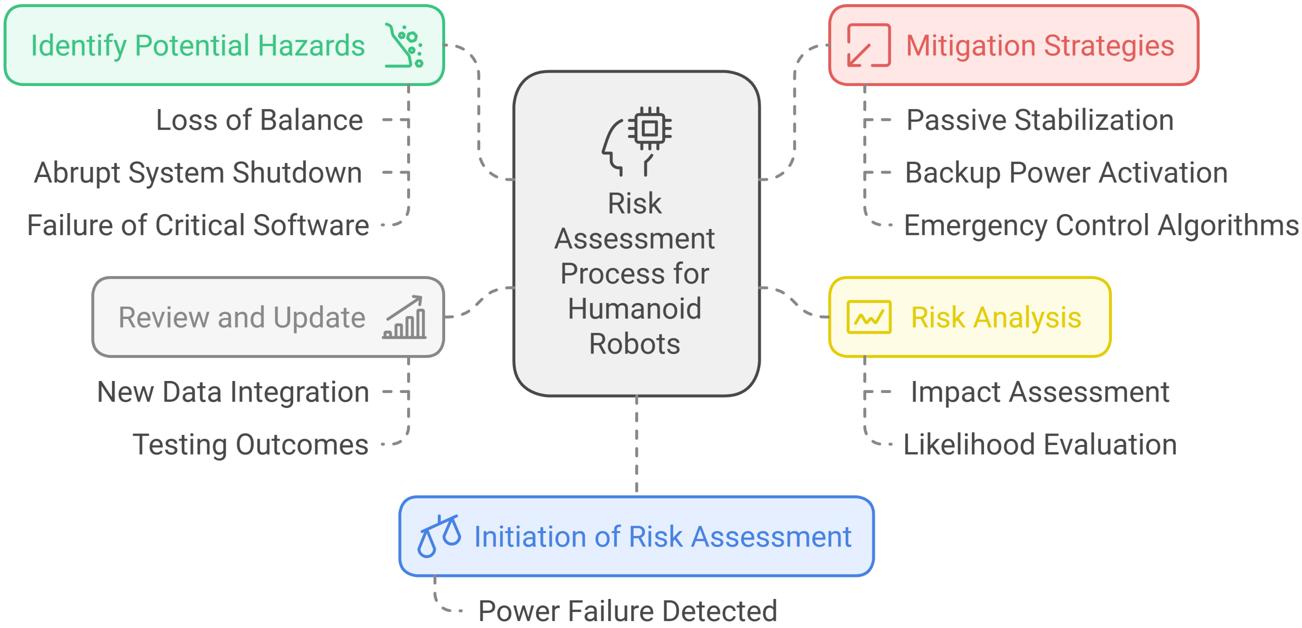

Fig. 1: Flowchart depicting the risk assessment process tailored for humanoid robots during power loss scenarios.

4) Monitoring of Proximity and Safe Distances:

- Protocol: Install monitoring systems using advanced sensors to assess the spatial separation between robots and human operators.
- Rationale: Continuous distance monitoring enhances safety in cooperative environments by preventing collisions when power is compromised [32].

5) Emergency Braking Mechanisms:

- Protocol: Equip humanoid robots with emergency braking systems that activate during power failures.
- Rationale: Such systems prevent unintentional movements or falls that could harm human operators and other equipment [42].

6) Real-Time Control Systems:

- Protocol: Utilize robust, real-time control frameworks capable of managing extensive data flows and providing immediate responses in emergency situations.
- Rationale: These frameworks facilitate the integration of preemptive safety algorithms that activate during power losses, ensuring timely intervention [7].

7) Enhancing Human-Robot Interaction Safety:

- Protocol: Follow the ISO/TS 15066 standards for collaborative robot operations, which include power and force limitation features.
- Rationale: Adhering to these guidelines minimizes injury risks during human-robot interactions within shared operational spaces [45].

8) Prioritization of Safety Based on Task Criticality:

- Protocol: Implement safety measures that are dynamically adjusted according to the critical nature of robot tasks.
- Rationale: This approach improves safety management while optimizing the utilization of energy and computational resources [42].

9) Synchronization of Safety and Control Systems:

- Protocol: Integrate safety protocols directly with control systems to modulate robot behaviors dynamically in crisis situations.
- Rationale: Such integration ensures a smooth transition to safe operational modes without sacrificing performance efficiency [46].

These strategic safety measures ensure that humanoid robots remain stable and mitigate hazardous incidents during power losses. These strategies encompass mechanical designs, software solutions, and operational tactics to minimize risk and augment reliability across various settings.

IV. Stability and Safety in Humanoid Robots

Designing humanoid robots to maintain stability and safety during power loss is paramount, necessitating robust mechanical frameworks and control strategies. Central to these strategies are passive stabilization mechanisms, which are essential for maintaining stability without active power inputs, particularly during emergency situations.

A. Mechanical Safety Enhancements

1) Passive Stabilization Techniques : Passive techniques are engineered to maintain stability and reduce the risk of falls or structural damage during power outages. Figure 2 showcases various passive mechanical solutions, such as locking joints and gravity-based supports, that ensure stability during power outages. Notable implementations include:

- Joint Locking Mechanisms: Devices such as electromechanical brakes effectively secure the robot's joints in the event of power failure, preserving its posture and preventing collapse. This principle is incorporated within stabilization models emphasizing safety and reliability, ensuring passive stability [5].
- Reduction of Center of Gravity: Constructing robots with a lower center of gravity significantly improves their inherent stability. This adjustment decreases the necessary torque for maintaining an upright position and improves balance capabilities. Techniques focusing on passive stability exploit the robot's mechanical structure to keep it within the bounds of the support polygon even when disturbed [1].
- Optimization of Support Polygon: Proactively or dynamically modifying the robot's support polygon ensures the center of mass is kept within stable boundaries. This adjustment can be mechanically executed by altering the placement of feet or other contact points to enhance stability [4].
- Integration of Energy-Absorbing Materials: Employing energy-absorbing materials in key structural areas diminishes the risk of mechanical failures during impacts, thereby supporting passive stability by cushioning potential damage.
- Simplified Inverted Pendulum Models: Conceptualizing humanoids as constrained inverted pendulums to restrict movements in unstable directions bolsters passive stability. Studies indicate simplified control models can sustain stability without power [47].

These passive stabilization techniques, including joint locking mechanisms, lowering the center of gravity, and optimizing support polygons, are critical for ensuring the mechanical safety of humanoid robots. Such strategies are fundamental in maintaining stability, significantly when power supply is compromised, thus forming an essential component of comprehensive safety frameworks.

2) Material and Design Strategies for Enhanced Stability : The design of humanoid robots to optimize stability in scenarios of power loss necessitates the selection of specific materials and structural configurations. These choices enhance mechanical characteristics and geometric alignments to support passive stability, thus enabling the robot to maintain balance independently of active power systems.

- Material Advancements for Stability
  - High-Damping Materials:
    - Viscoelastic polymers, utilized in joint cushions and for structural reinforcement, exhibit excellent energy absorption qualities. These materials are pivotal in mitigating energy transfer during impacts or abrupt movements, enhancing stability.
    - Such high-damping materials are proven to reduce oscillations significantly, a vital feature when control systems are inactive [5].
  - Lightweight Alloys:
    - Utilizing titanium alloys and carbon fiber composites reduces the robot's overall weight while preserving its structural integrity. The reduction in mass decreases the moment of inertia, facilitating quicker stabilization following external perturbations [4].
  - Elastic Actuators and Structural Flexibility:
    - Incorporation of elastic materials in joint areas allows for a controlled degree of flexibility, aiding the robot in adjusting to unforeseen shifts in load or posture without the risk of collapse. These elements are passive buffers during power outages [48].
- Structural Design Enhancements for Stability
  - Lower Center of Gravity (COG): o Strategically lowering the robot's center of gravity enhances its stability. Design approaches that aggregate mass in lower regions, such as through denser leg components or weighted foot designs, expand the stability base during power interruptions [1].
  - Expanded Support Polygon: o Broadening the support base, perhaps through more significant or adaptable foot mechanisms, augments the stability margin. Robots with broader feet or additional support points exhibit a reduced propensity for tipping under unstable conditions [4].
  - Optimized Geometric Configurations: o Tailoring the design of limbs and body segments to foster stability under gravitational forces, with features like extended legs or compact torsos, minimizes tipping risks. Such configurations are inspired by biological mechanisms observed in bipedal organisms [47].
  - Modular and Distributed Weight: o Evenly distributing weight throughout the robot's framework helps prevent destabilizing torques during shifts or disturbances. Modular design also permits adjustments in the robot's mass distribution to counterbalance potential instability [7].
  - Integrated Energy Reserves: o Incorporating passive energy reservoirs within the robot's joints or torso provides a crucial energy source for stabilizing movements during transitions, ensuring continuous operation even when power is compromised [47].

The strategic application of innovative materials and thoughtful structural designs is essential for bolstering the stability of humanoid robots during power-loss situations. Employing materials with high damping properties, lightweight alloys, and design optimizations such as a low center of gravity and an expanded support polygon collectively form a strong foundation for safety and stability in challenging operational environments.

B. Electrical and Control Strategies

1) Integration of Redundant Power Systems and Emergency Energy Reserves : Robust electrical frameworks, including redundant power systems and emergency energy storage mechanisms, are imperative to achieve stability in humanoid robots during power disruptions. These systems maintain operational

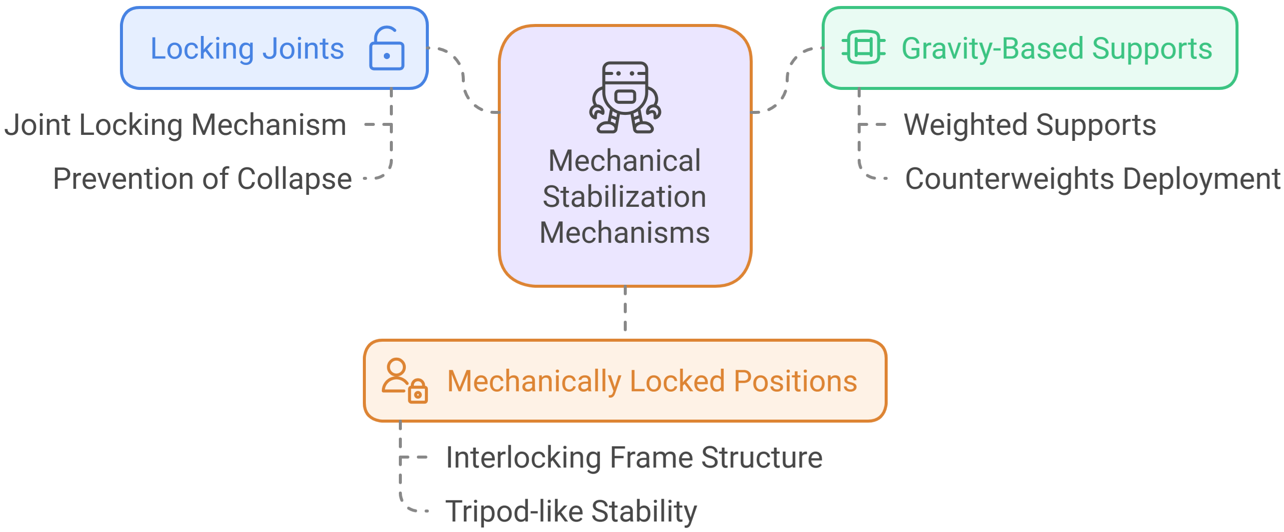

Fig. 2: Schematic of mechanical stabilization mechanisms designed to maintain robot stability without power.

continuity by ensuring backup power availability and enhancing energy management efficiency.

- Redundant Power Systems
  Redundant power configurations employ multiple independent power sources that collectively contribute to uninterrupted robot functionality during power outages or system failures.
  - Hybrid Energy Configurations: o Robots can be equipped with various power sources, such as lithium-ion batteries, fuel cells, or capacitors, to provide a broad spectrum of power availability. Such hybrid configurations facilitate seamless energy shifts during power disruptions [49].
  - Decentralized Energy Systems: o Mirroring natural biological systems and deploying energy sources throughout the robot's structure increases the reliability and stability of operations. This decentralized approach diminishes the reliance on a single power source, reducing the chances of complete operational failure [50].
  - Fail-Safe Redundant Mechanisms: o Systems designed with redundancy can continue functioning even when a primary power source fails. These mechanisms are engineered to reroute energy to essential functions, thus bolstering the robot's fail-safe capabilities [51].
- Emergency Energy Storage
  Emergency energy reserves are critical for providing immediate auxiliary power to avert sudden operational halts during essential tasks.
  - Flywheel Energy Storage: o Flywheel technology harnesses kinetic energy, converted into electrical power during interruptions, ensuring continuity in robot activities during emergencies [52].
  - Mechanical Energy Storage via Magnetic Springs: o Magnetic spring systems accumulate mechanical energy that can be swiftly utilized during power losses, thus optimizing energy use and improving system reliability [53].
  - Hybrid Battery and Supercapacitor Units: o The integrating batteries with supercapacitors offers an efficient energy management solution, prolonging operational life. Supercapacitors provide rapid energy bursts, complemented by the battery's sustained energy output [54].
  - Dynamic Wireless Energy Transfer: o Innovative wireless power systems enable robots to recharge while mobile, minimizing downtime and decreasing dependence on extensive battery configurations [55].

The deployment of redundant power systems along with emergency energy storage solutions is essential for maintaining humanoid robots' stability and operational integrity in scenarios where power availability is compromised. These systems bolster resilience by utilizing mixed energy sources, decentralized energy layouts, and advanced storage technologies such as flywheel systems and supercapacitors.

2) Deployment of Failsafe Control Algorithms for Power Interruptions : Failsafe control algorithms are essential in maintaining humanoid robots' stability and safety during power loss. These algorithms swiftly adapt to such disruptions by activating alternate control measures to preserve balance and avert structural damage. Figure 3 details the control algorithm that initiates emergency protocols to maintain balance and functionality immediately following a power interruption.

- Principal Failsafe Control Strategies
  - Adaptive and Resilient Controls: Adaptive control systems, utilizing real-time estimation capabilities, dy-

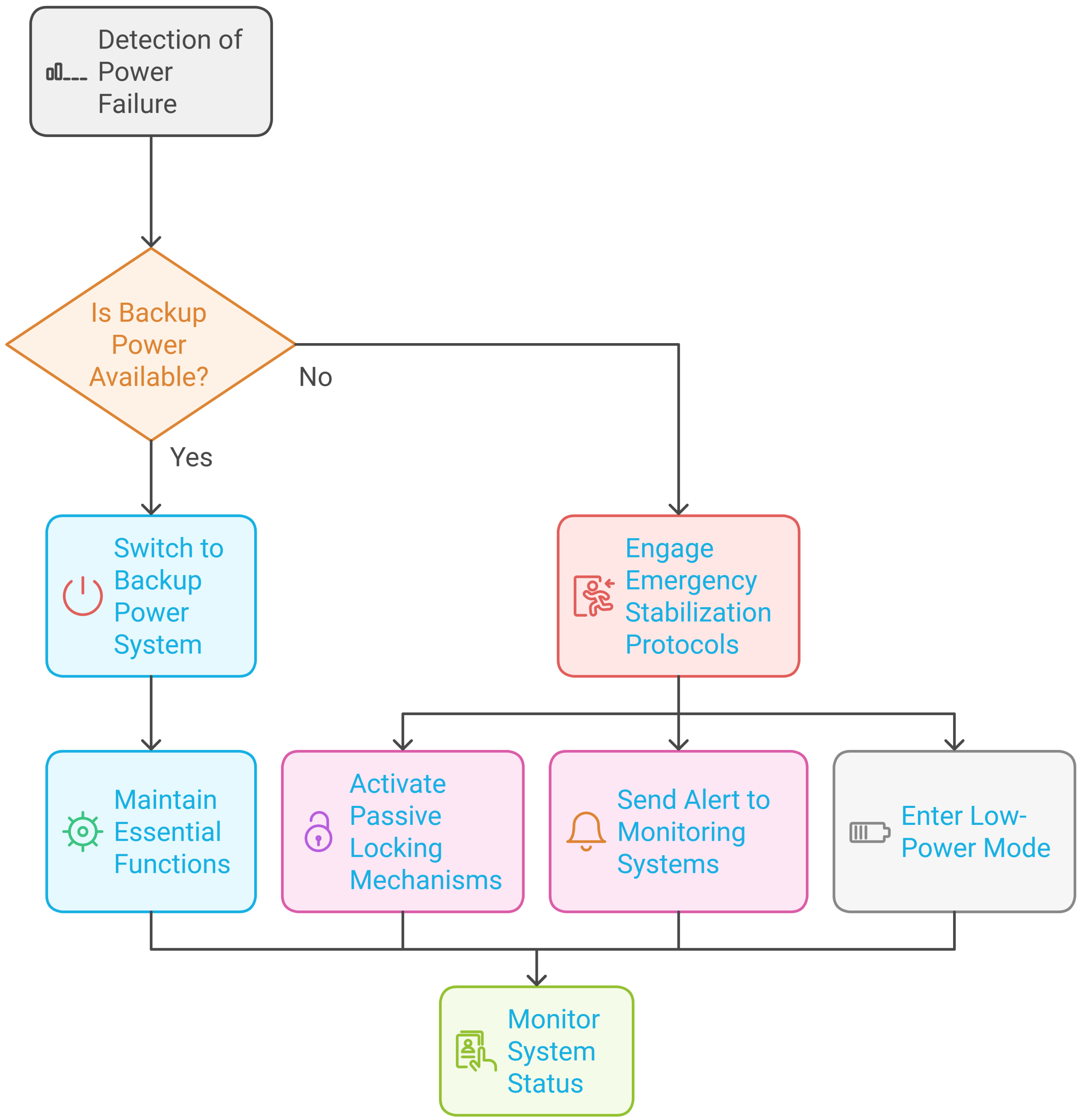

Fig. 3: Flowchart of the control system algorithm for detecting and responding to power failures.

namically recalibrate to suit changing conditions during power outages. For instance, a model-free robust adaptive control employs time-delay estimation to mitigate disturbances and uphold stability [56].

– Layered Control Systems: Hierarchical control systems facilitate real-time momentum management, which sustains stable operation even amidst external disruptions or power deficiencies. This structure supports momentum-oriented task management, significantly enhancing robustness [57].

– Predictive Control in Real-Time: Predictive control mechanisms, such as model predictive control (MPC), predict and modulate robot dynamics to maintain equilibrium and stability, utilizing immediate feedback to

adapt swiftly to evolving conditions [58].
  - Anomaly Detection and Response: Systems designed to monitor essential variables like motor velocity and energy circulation promptly identify deviations. Upon detection, fault-tolerant controls, such as momentum-based systems, stabilize the robot. Notably, momentum-based control has proven effective in managing propulsion anomalies in jet-powered humanoid robots [59].
  - Decentralized and Modular Controls: The decentralization of control systems enhances robustness by segmenting subsystems and reallocating energy to vital components during failures. These configurations utilize localized controllers for immediate adjustments, bolstering dynamic response capabilities [60].
- Illustrations of Algorithmic Implementations
  - Neural Network-Driven Failsafe Mechanisms: Neural networks dynamically learn and adapt to unforeseen power outages by analyzing historical performance data, enabling robots to respond efficiently even without preset directives [61].
  - Fuzzy Logic for Enhanced Decision-Making: Fuzzy logic controllers interpret ambiguous conditions, such as power interruptions, and implement established fail-safe maneuvers to stabilize robot operations. Fuzzy logic has effectively handled complex movements involving multiple degrees of freedom [62].
  - Redundant Mechanical Actions: Integrating additional actuators and torque mechanisms allows robots to distribute operational loads during power failures, thus minimizing strain on essential systems and ensuring continued stability [63].

Failsafe control algorithms, encompassing adaptive and resilient controls, hierarchical frameworks, and predictive mechanisms, are crucial for the reliable operation of humanoid robots under power failure conditions. By utilizing distributed and modular controls, intelligent decision-making technologies, and redundant mechanical systems, these algorithms fortify the robots against unexpected disturbances, ensuring operational continuity and structural integrity.

C. Safety and Reliability Enhancements

1) Adoption of DO-178C Software Standards for Enhanced Fail-Safe Performance : DO-178C, the benchmark standard for safety-critical airborne software systems, presents a set of stringent guidelines that are equally beneficial for advancing software reliability in humanoid robots, particularly for ensuring robust operations during power disruptions. The framework of DO-178C is built around comprehensive software design, development, testing, and validation protocols, with a strong emphasis on safety and traceability.

- Applicability of DO-178C Standards in Humanoid Robotics
  - Assurance and Verification in Design: DO-178C prescribes a methodical software development process that demands traceability from the initial requirements to implementation and subsequent verification. This process ensures that every critical safety function is rigorously tested against its specified requirements, thereby boosting the reliability of robotic control systems [64].
  - Qualification of Development Tools and Automation: Tools utilized in the development phase, particularly in model-based designs such as those employed in humanoid robotics using MATLAB/Simulink, must meet DO-178C qualifications to verify they do not introduce errors during software creation and validation [65].
  - Model-Based Development and Adherence: Supplement DO-331 under DO-178C offers guidance on model-based development, an approach prevalent in robotics. This framework enables developers to simulate robot behavior in varied failure scenarios, ensuring the system's robustness [66].
  - Employment of Formal Methods in Critical Software: Formal verification methods, as specified in DO-333, a supplement to DO-178C, are crucial for confirming the accuracy of critical software components. These techniques help detect and resolve potential software anomalies in robotic systems prior to deployment [67].
  - Reliability and Fault Tolerance Measures: Emphasizing error detection, isolation, and recovery strategies, DO-178C standards are particularly relevant to humanoid robots, providing mechanisms for safe system shutdowns or controlled operations during failures [68].
- Examples of Practical Implementations
  - Real-Time Software Frameworks: Implementing real-time interprocess communication within modular architectures that align with DO-178C helps enhance overall system robustness by confining software errors to isolated modules. These architectures are implemented in humanoid robot control systems to guarantee safe functionality [69].
  - Standard Compliance in Systems with Multiple Actuators: The application of DO-178C in control algorithms for humanoid robots, especially those with multiple actuators, ensures coordinated operations, fault recovery, and consistent functionality across all mechanical joints, mitigating risks during crucial operations [7].
  - Protocols for Safety-Critical Testing: Testing environments compliant with DO-178C standards, designed to simulate power outages and control disruptions, validate that robots can restore normal operations safely without causing harm or system damage [70].

Integrating DO-178C standards into the software development lifecycle of humanoid robots facilitates robust, fail-safe operations through meticulous design, verification, and testing protocols. Adherence to these guidelines substantially improves the reliability and safety of humanoid robots, particularly in scenarios characterized by unexpected power losses.

2) Advanced Algorithms for Dynamic Balance and Immediate Power Fluctuation Response: Humanoid robots employ sophisticated algorithms that combine real-time feedback, predictive models, and adaptive controls to secure dynamic balance and swiftly address power fluctuations. These algorithms are crucial for enabling robots to sustain stability and prevent falls amidst power interruptions or when encountering external disturbances.

- Essential Algorithms for Dynamic Balance Control:
  - Zero Moment Point (ZMP)-Based Control: ZMP is vital for dynamic balance, where algorithms calculate the point at which the total moment from inertial forces becomes zero. This technique ensures that the robot's center of gravity remains within its support base, thus averting falls [71].
  - Dynamic Balance Force Control (DBFC): DBFC algorithms adjust joint torques based on the desired motion of the center of mass (COM) and the contact forces exerted. These adjustments help maintain a stable balance despite considerable disturbances [72].
  - Hierarchical Whole-Body Control (WBC): WBC arranges control tasks hierarchically, giving precedence to balance over other tasks such as manipulation or movement. This strategy employs real-time optimization to calculate joint torques necessary for maintaining stability during dynamic actions [73].
  - Momentum-Based Balance Control: These controllers handle linear and angular momentum to stabilize the robot under various scenarios, like uneven or shifting surfaces. The focus is on managing linear momentum to prevent falls, sometimes at the expense of angular stability [74].
- Rapid Response to Power Variations:
  - Model Predictive Control (MPC): MPC uses dynamic models to forecast the robot's future states and adjust its movements to stabilize accordingly. This forward-looking approach ensures the robot maintains balance during sudden power changes or external impacts [75].
  - Sensor-Driven Adaptive Control: Algorithms utilize real-time data from sensors, such as gyroscopes and accelerometers, to tailor joint movements that counterbalance instabilities. These adaptive systems have demonstrated strong resilience to disturbances in trials on platforms like the Walker3 humanoid robot [76].
  - Reactive Control Systems: Employing threshold-based and hybrid controls, these algorithms react instantaneously to unexpected changes by triggering preprogrammed recovery actions. These model-free methods, which replicate successful past responses, prove effective for stabilization on irregular terrain [77].
  - Task-Prioritized Dynamic Balancing: Algorithms prioritize tasks dynamically, adjusting joint movements to maintain balance and avoid collisions with the robot. Techniques for momentum compensation are employed to neutralize unforeseen disturbances during intricate maneuvers [78].
- Experimental Validation:
  - Dynamic Environments: Tests with systems like Walker3 validate the effectiveness of WBC and adaptive controllers in managing multiple disturbances concurrently, including tilts, shifts, and external shocks [73].
  - High Responsiveness: Utilizing sensor fusion and predictive modeling, these algorithms enable robots to sustain stability in highly dynamic environments, such as balancing unstable platforms like seesaws [79].

By implementing dynamic balance control algorithms such as ZMP-based, DBFC, hierarchical WBC, and immediate response mechanisms, humanoid robots can maintain stability and responsiveness during power fluctuations. These advanced systems ensure the robots' resilience and adaptability in predictable and unpredictable conditions.

V. Safety Integration Protocols

The comprehensive framework established by integrating ISO 10218, ISO/TS 15066, ISO 13482, DO-178C, and DO-254 encapsulates a multi-dimensional approach to the safety of humanoid robots by addressing their mechanical, software, and operational facets. ISO 10218 and ISO/TS 15066 are pivotal in delineating the mechanical safety and risk assessment parameters essential for human-robot interaction. In contrast, ISO 13482 targets the safety nuances specific to personal care robots. Concurrently, DO-178C and DO-254 are instrumental in fortifying the reliability of software and hardware, respectively, reinforcing the foundation of functional safety in robotic applications, as documented by Harper & Virk [80].

The harmonious interaction between these standards fosters a robust safety network that effectively mitigates hazards, manages collision risks, and establishes reliable fallback protocols. For instance, integrating risk assessment protocols from ISO 10218 with the force-limiting capabilities of ISO/TS 15066 enhances safety measures for direct interactions between humans and robots, as explored by Rosenstrauch & Krüger [11].

A. *Mechanical and Software Safety Integration*

1) Implementation of ISO 10218 and ISO/TS 15066 : ISO 10218 solidifies the foundation for mechanical safety and risk management and underscores the importance of real-time monitoring and the integration of emergency stop mechanisms. Complementing this, ISO/TS 15066 introduces adjustments centered on human safety, including mechanisms that limit power and force, thereby reducing risks in cooperative environments, as noted by Rampa et al. [10].

- Emergency Response Mechanisms: Systems capable of real-time hazard recognition are integrated with mechanical actuators to facilitate immediate responses, either by halting operations or reducing force, thereby enhancing safety under adverse conditions [9].
- Fallback Protocols: Mechanical supports, like gravity-based or mechanically locked positions, ensure the stability of robotic systems in the event of power failures. These designs adhere to the robustness criteria set forth by ISO 10218, while the addition of ISO/TS 15066 addresses the management of residual forces to safeguard human operators during emergencies [81].
- Collaborative Interaction Zones: The frameworks for risk analysis from ISO 10218 and ISO/TS 15066 define safe operational zones, employing proximity sensors to

minimize the risk of collisions, thereby securing a safer environment for human-robot interaction [35].

Such integrative efforts enhance the multilayered safety strategies, significantly elevating the operational reliability of humanoid robots across various settings.

2) Enhancements in Control Systems: Addressing Power-Loss Scenarios: The design of control systems in humanoid robots encompasses mechanisms to recognize and respond to power interruptions promptly, thereby adhering to safety protocols delineated by ISO/TS 15066 and ISO 10218. These enhancements bolster system robustness and safeguard operator safety under unexpected power outage conditions. The principal strategies implemented are as follows:

- Rapid Detection of Power Interruptions: State-of-the-art sensors and control units are pivotal in monitoring electrical supply variations. These components activate necessary measures to uphold system stability. Notably, the application of control barrier functions enables real-time adjustments in the robot's behavior to stay within safe operational bounds, as Ferraguti et al. [81] outlined.
- Activation of Pre-established Stability Measures: In the event of power failures, robots are programmed to revert to pre-defined safety states that include:
  - Gravity-Assisted Safe Configurations: Robots are equipped with mechanical designs that lock joints or utilize gravitational forces to maintain stability, as Golshani et al. [45] developed.
  - Energy Reserve Strategies: These systems conserve energy and redistribute it to sustain critical operations temporarily, allowing time for other safety protocols to activate, as Benzi et al. [82] explored.
- Adjustments in Real-Time Control:
  - Control systems such as Sliding Mode and Model Predictive Control (MPC) ensure continued performance against external disturbances, maintaining system stability and accurate motion control during power disruptions [83].
  - Adaptive force controllers, employing variable impedance techniques, dynamically modify force outputs to suit fluctuating demands, aligning with ISO/TS 15066's requirements [84].
- Mechanisms for Safe State Transitions: These systems are critical in mitigating risks during power loss by:
  - Employing dynamic planners that ensure a collision-free trajectory, thus preventing any unintended movements [83].
  - Integrating Speed and Separation Monitoring (SSM) that adjusts robot operations dynamically in relation to the proximity of human operators, ensuring compliance with established safety standards [10].

These control system enhancements significantly increase the resilience and adaptability of humanoid robots, effectively managing power-loss scenarios to ensure both safety and operational continuity.

B. Advancements in Human-Robot Interaction Safety

1) Implementing Enhanced Safety Protocols for Direct Human-Robot Interaction : The standard ISO 13482 outlines crucial safety protocols for personal care robots, emphasizing the necessity for secure human-robot interactions. These robots are designed to consider both the physical and cognitive dimensions of human interactions to safeguard against injuries during routine activities, including during power failure. Essential safety protocols include:

- Proactive Risk Management: Equipped with sensors and sophisticated control mechanisms, these robots continuously scan their operational environment to foresee and neutralize potential hazards. This includes detecting human presence and adjusting functionalities to accommodate immediate circumstances [15].
- Limitation of Force and Power: Adhering to safety guidelines such as those specified in ISO 13482, these robots are engineered to operate within defined force thresholds when in close contact with humans, ensuring safety during physical interactions [16].

2) Enhancing Safety in Robot Mobility : For personal care robots, mobility is critical; therefore, advanced systems are in place to maintain safety and stability, especially in the event of power loss:

- Stability Control:
  - Adaptive control systems are crucial for dynamically adjusting the robot's center of gravity, ensuring balance and stability are maintained even during a power outage [9].
  - Design strategies utilize gravity-assisted supports to secure the robot in a stable position, preventing falls by locking it into the last known safe configuration [45].
- Fall Prevention Strategies:
  - Equipped with accelerometers and gyroscopes, these robots can detect and respond to any imbalance or shifts, activating rapid-response systems to initiate safety measures [82].
  - Including active braking systems within the mobility framework of the robot provides essential control over movement when power is compromised [80].

3) Focus on Human-Centric Safety Design:

- Interaction Sensors for Safety: Integrating tactile and proximity sensors allows the robot to perceive physical interactions, thereby adjusting the exerted force to safe levels during close encounters. This is particularly crucial in environments where personal care robots operate closely with humans [16].
- Safe Configuration Protocols: Robots are programmed to adhere to ISO 13482 standards, enabling automatic adjustments such as limb retraction or transitioning to low-risk positions during power failures, effectively minimizing potential dangers [15].

These advancements in human-robot interaction safety, guided by ISO 13482, incorporate strategies for proactive risk management, integrated safety features for enhanced mobility, and human-centric design principles. Collectively, these measures ensure that personal care humanoid robots interact safely with humans, maintaining operational stability and minimizing risks even during unforeseen power losses.

C. Enhancing Software and Hardware Dependability

1) Application of DO-178C and DO-254 in Robotic Systems : The standards DO-178C and DO-254 play pivotal roles in fortifying the software and hardware dependability of safety-critical systems, such as humanoid robots. These standards are instrumental in developing systems that remain functional and safe during interruptions in the power supply.

2) Software Resilience Under DO-178C : DO-178C offers a systematic approach to crafting robust software that operates reliably, particularly under compromised power conditions:

- Redundant Software Mechanisms:
  - Essential software components, crucial for maintaining balance and controlling motor functions, are engineered to have redundant counterparts, ensuring they operate during a power failure [85].
  - Software designed to be fail-operational maintains stability and facilitates orderly shutdowns during emergencies [81].
- Adaptation to Low-Power States:
  - Specific algorithms are tailored to adjust the robot's behavior under low power, optimizing energy usage while preserving vital functions such as balance and anti-fall mechanisms [45].
- Rigorous Testing and Validation:
  - Adhering to DO-178C, comprehensive testing regimes validate the software's adherence to safety standards and its performance reliability across various scenarios, including simulated power disruptions [83].

3) Ensuring Hardware Integrity with DO-254 : DO-254 delineates rigorous hardware design standards to guarantee reliability in the event of power outages:

- Hardware Designed for Power Interruptions:
  - Critical hardware elements like gyroscopes, accelerometers, and actuators have individual power solutions or capacitors to furnish short-term energy during power disruptions [82].
  - The system incorporates hardware redundancies, ensuring backup mechanisms activate to support essential functions, such as joint stability and mobility control.
- Validation and Regulatory Compliance:
  - Under DO-254, hardware undergoes fault injection tests to simulate power failures and verify operational stability [80].
  - Integrated diagnostics capabilities facilitate early detection of potential faults to prevent system failures.
- Managed Energy Dissipation:
  - Hardware integrates systems like energy tanks to manage and dissipate residual energy effectively, ensuring that shutdowns are controlled and stability is maintained during power failures [82].

Integrating DO-178C and DO-254 in the development process underpins software and hardware reliability, enabling humanoid robots to effectively manage and mitigate the effects of power-loss situations. These standards foster the creation of fail-safe systems that prioritize continuous operation and stability, thus safeguarding the robot's functionality and the safety of its operational environment.

4) System Redundancy: Designing for Continual Power Supply : The architecture of redundant power systems is critical for maintaining essential functions in humanoid robots during power interruptions:

- Segregated Power Systems:
  - Power distribution is strategically segmented, with separate battery packs designated for control systems and motor operations, allowing the robot to uphold stability and engage safety measures during a power outage [86].
  - Dynamic power allocation enhances the robot's capacity to prioritize critical functions under limited power availability.
- Wireless Energy Reception:
  - Systems designed to harvest power wirelessly, such as robots equipped with "power shoes" that draw energy from a floor-based "power mattress," extend operational capacity briefly even when conventional battery power wanes [87].

5) Alternative Energy Provisions : Backup energy solutions, including fuel cells and hybrid systems, complement the redundant power designs to extend operational time during power outages:

- Integration of Fuel Cells:
  - Direct Methanol Fuel Cells (DMFCs) provide sustained energy output, supporting robot operations for extended periods during emergencies, complemented by batteries for peak load management [88].
  - These fuel cell systems are especially suited for environments where noise and emissions must be minimized.
- Capacitive Energy Storage:
  - High-capacity capacitors are immediate power reserves during outages, facilitating stable transitions to safe operational states. These are essential in systems that require quick responses to power fluctuations [82].

6) Strengthening System Resilience :

- Hybrid Power Solutions:
  - Combining traditional battery systems with renewable energy sources or fuel cells enhances operational longevity and reliability, with electronic filters ensuring smooth power transitions [89].
- Advanced Fault Management:
  - Multi-sensor power monitoring systems identify power supply irregularities, isolate faults, and maintain consistent energy supply to critical components, effectively minimizing disruption [90].

By implementing redundant power arrangements and robust backup energy sources, humanoid robots are equipped to sustain critical operations and ensure stability control during power outages. These technological enhancements align with industry standards and are crucial for promoting operational continuity and enhancing safety in robotic applications.

D. Development and Validation of Theoretical Analysis

1) Constructing a Theoretical Framework : Establishing a theoretical framework that integrates critical safety features within humanoid robots draws upon diverse safety and reliability standards, including ISO 10218, ISO/TS 15066, ISO 13482, DO-178C, and DO-254. These guidelines collectively address the various facets of mechanical integrity, operational safety, software reliability, and hardware robustness, forming an encompassing protocol for safety. Figure 4 depicts a theoretical integrated framework developed for humanoid robots in case of power outage.

- Theoretical Underpinnings:
  - ISO 10218 and ISO/TS 15066: Mechanical Safety and Operational Compliance
    - Focus: These standards enhance safety in environments where robots and humans collaborate, emphasizing physical risk mitigation, advanced collision detection, and stringent controls on force and energy exerted during interactions [9].
    - Application: Theoretical models based on these standards include:
      - Systematic risk evaluations to forecast and manage potential hazards inherent in robotic operations [11].
      - Adaptive control mechanisms that regulate speed and force, aligning with safety requirements for collaborative workspaces [91].
  - ISO 13482: Safety in Human-Robot Interaction for Personal Care
    - Focus: This standard specifies safety measures for service robots within personal care settings, ensuring adaptability and protection in human-centric applications [16].
    - Application: Theoretical approaches involve:
      - Biomechanical analysis to determine acceptable force levels during physical interactions.
      - Integration of proximity sensors and emergency protocols to maintain safety during unforeseen events [80].
  - DO-178C and DO-254: Ensuring Reliability in Software and Hardware
    - Focus: DO-178C focuses on software development for critical systems, whereas DO-254 emphasizes hardware reliability [45].
    - Application: The frameworks include:
      - Software designs that ensure robots remain operational, transitioning safely during power interruptions.
      - Architecture incorporating hardware redundancy and fault tolerance support continuous operation [82].
- Synthesis of Safety Principles into Comprehensive Protocols:
  - Integrated Hazard Management: o By merging risk assessment techniques from ISO/TS 15066, ISO 10218, and DO-178C, mechanical and software-related risks are comprehensively managed. This approach utilizes tiered hazard control measures that allow robots to dynamically identify, address, and mitigate risks [81].
  - System Redundancies: o Models incorporating redundant energy storage and control mechanisms, guided by ISO 13482 and DO-254, ensure that safety-critical functions remain operational during system failures [86].
  - Continuous Monitoring and Adaptive Control: Advanced sensors and algorithms continuously monitor system performance and adjust robotic actions based on real-time data regarding human proximity and overall system status [83].
  - Validation via Simulation: Theoretical models are tested through simulations that mimic power-loss conditions to assess and refine the robot's responses to ensure compliance with safety standards [80].

This theoretical framework combines principles from ISO and DO standards to equip humanoid robots with robust, layered safety protocols. These protocols are crucial for ensuring that robots maintain operational integrity, effectively manage hazards, and safeguard human interactions, particularly during power disruptions.

2) Analytical Methods for Robotic Design Validation:

- Utilization of Analytical Methods for Comprehensive Validation
  Analytical methods are essential in verifying humanoid robots' mechanical integrity, control system efficacy, and emergency responsiveness, particularly under conditions where power is compromised. These methods incorporate mathematical modeling and logical analysis to predict and assure system performance, aligning with established safety standards.
- Mechanical Integrity Validation
  - Analysis of Structural Components:
    - Finite Element Analysis (FEA) is pivotal in evaluating the durability and structural soundness of key components like robot joints and frames, especially in abrupt power outages. This technique helps pinpoint potential vulnerabilities, ensuring the robot's architecture can endure unexpected loads [11].
    - The functionality of gravity-assisted fallback mechanisms is scrutinized through analytical kinematics, verifying their capability to secure or stabilize the robot's position during potential free falls or instability [45].
  - Modeling of Energy Dissipation:
    - Energy dissipation models calculate the forces ab-

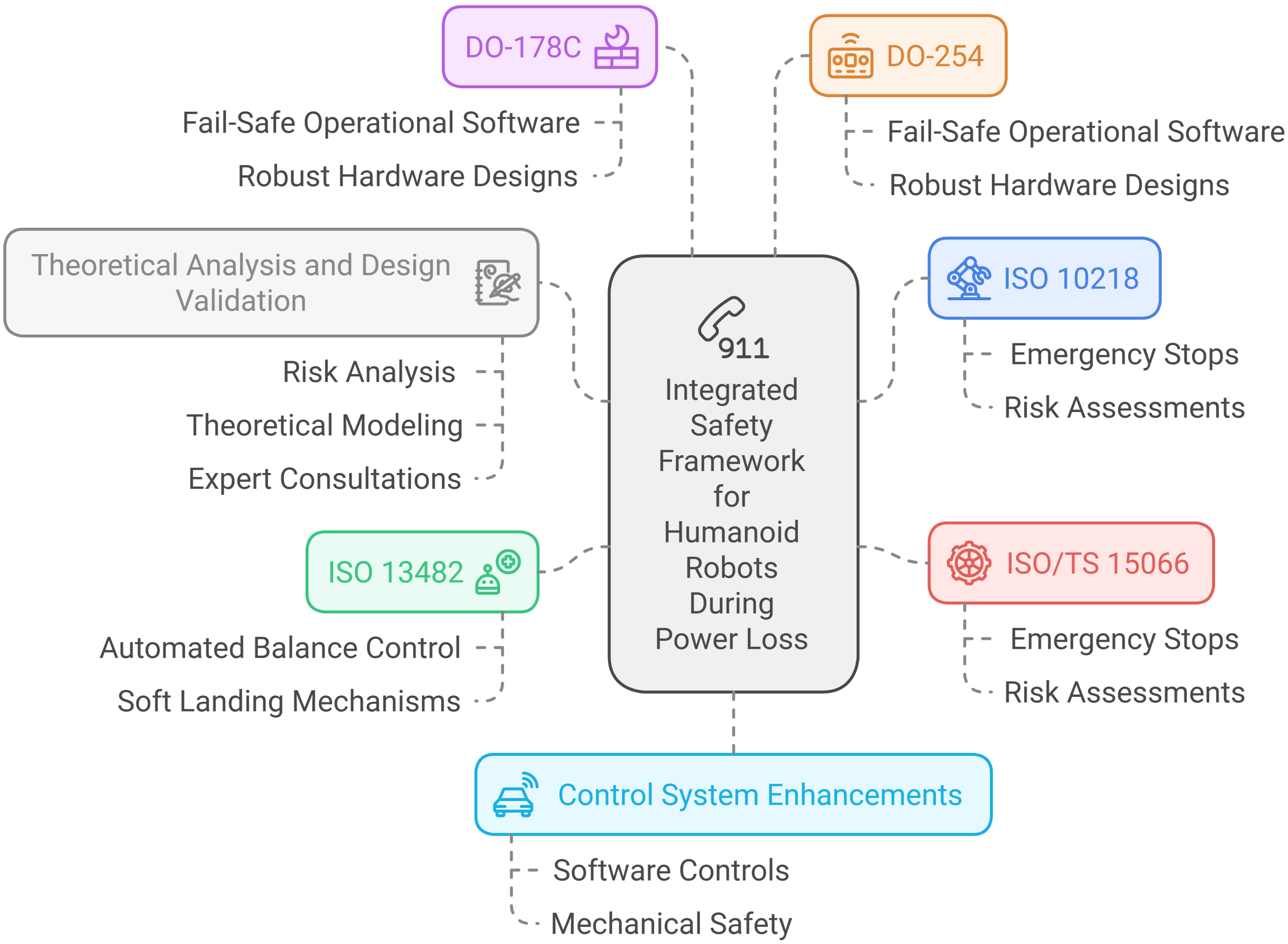

Fig. 4: A theoretical integrated framework development for humanoid robots amid power loss.

sorbed by systems such as energy tanks or mechanical dampers, validating their effectiveness in adhering to biomechanical safety norms [82].

- Control System Reliability Validation
  - Simulation of Dynamic Systems:
    * The reliability of control systems during power interruptions is assessed through simulations based on state-space models and differential equations. These simulations are crucial for verifying that emergency protocols activate within designated timeframes [81].
    * The performance of proximity-based safety algorithms, which are critical under reduced power conditions, is tested to ensure they maintain safe human-robot interactions, guided by the parameters of ISO/TS 15066 [91].
  - Testing for Redundancy:
    * Logical analyses confirm the autonomy and duplication of essential control functions, ensuring that secondary systems initiate effectively when primary systems falter [86].
- Emergency Response Feature Validation
  - Mathematical Modeling of Emergency Protocols:
    * Mathematical models are used to determine the efficiency of emergency braking systems, calculating safe stopping distances to prevent the robot from tipping over under various conditions [83].
    * Predictive control models are scrutinized to ascertain their capacity to adjust joint positions and preserve balance during power disruptions.
  - Risk Mitigation Analysis:
    * Fault tree analysis methodically evaluates potential failure modes within emergency response systems, ensuring that all risks are adequately countered with mechanical or software-based safeguards [9].
- Evaluating Power-Loss Scenario Effectiveness
  - Probabilistic Safety Assessments:
    * Monte Carlo simulations estimate the probability of

successful system recovery under different power-loss conditions, identifying designs that might be prone to failure [88].

- Iterative Design Refinement:
  * Continuous refinement of designs through analytical predictions and empirical testing cycles helps align theoretical models with actual performance, ensuring robustness and reliability in real-world applications [80].

Through the strategic application of analytical methods, the design validation of humanoid robots encompasses rigorous assessments of mechanical structures, control systems, and emergency features. These methodologies enable designers to predict system behaviors and effectively refine safety mechanisms in power failure scenarios, aligning with international safety standards and ensuring comprehensive robot safety.

3) Risk Evaluation and Mitigation Planning:

- Identifying and Analyzing Risks
  In scenarios where humanoid robots face power disruptions, various risks arise, including mechanical failure, control loss, and collision dangers. Risk evaluation involves utilizing theoretical models to anticipate potential failures and devise strategies to mitigate these risks effectively.
  - Risk Identification:
    * Potential hazards such as falls, uncontrollable movements, or complete system shutdowns are pinpointed based on typical operational scenarios, particularly assessing the effects of power loss on joint functionality and mobility [9].
    * Analysis also includes evaluating risks associated with human interactions, such as the impact of collisions and proximity-related dangers [16].
  - Quantitative Risk Analysis:
    * Analytical techniques like Fault Tree Analysis (FTA) and Failure Mode and Effects Analysis (FMEA) quantify risks and determine the significance of various failure modes, highlighting areas that require reinforced safety measures [80].
    * Probabilistic assessments, including Monte Carlo simulations, estimate the likelihood of potential failures under different power loss conditions [88].
- Developing Mitigation Strategies Strategies to mitigate identified risks are crafted to ensure humanoid robots' safety and functionality during power supply interruptions.
  - Systems with Redundancy:
    * Power System Redundancy: Integrating alternative energy sources, such as batteries or fuel cells, supports the continuous functionality of critical systems during power failures [89].
    * Control System Redundancy: Auxiliary control units are prepared to activate if primary systems fail, preserving crucial stability operations [86].
  - Emergency Response Protocols:
    * Automatic Fallback Configurations: Robots are engineered to automatically shift to locked or stable low-risk positions when power is lost, ensuring stability and safety [81].
    * Energy Dissipation Mechanisms: Energy tanks are designed to safely manage and neutralize residual energy, preventing sudden movements or collapses [82].
  - Adaptive Control Technologies:
    * Real-time control algorithms dynamically adjust joint positions and movement speeds to maintain equilibrium, even during abrupt drops in power [83].
- Role of Risk Assessment in Design
  - Influencing Design Priorities:
    * Risk assessments direct the focus of design efforts, ensuring that vital safety features such as collision avoidance and structural integrity are effectively integrated [91].
    * Safety standards like ISO 10218 and ISO/TS 15066 set the criteria for developing systems that facilitate safe human-robot interactions [11].
  - Simulation-Driven Validation:
    * Theoretical models are employed to confirm the effectiveness of mitigation strategies, minimizing the reliance on physical trials by predicting performance in simulated environments [80].
    * Simulations using advanced state-space and kinematic models verify that emergency responses are consistent with theoretical expectations [83].

The structured approach of risk analysis and the development of corresponding mitigation strategies form a critical foundation for ensuring the safety of humanoid robots during power losses. By leveraging theoretical modeling and risk assessment, the design process is guided towards addressing and resolving safety challenges efficiently, aligning with international safety standards and reducing the necessity for extensive empirical testing. This methodology underpins a proactive stance in robot safety management, prioritizing preemptive action over-reactive measures.

4) Enhancing Design through Peer Review and Expert Consultation:

- Leveraging Peer Review Feedback
  Peer review plays a pivotal role in validating theoretical constructs and practical applications within safety frameworks designed for humanoid robots. Input from domain experts in robotics, software reliability, and safety engineering is critical to thoroughly evaluating proposed safety mechanisms.
  - Organized Peer Review Methodology:
    * Interdisciplinary Review Panels: The inclusion of experts from varied disciplines, such as mechanical engineering, control systems, and human-robot interaction (HRI), guarantees a comprehensive evaluation of all design aspects [80].
    * Consistent Evaluation Standards: Employing established safety standards such as ISO 10218, ISO/TS

15066, ISO 13482, DO-178C, and DO-254 ensures a uniform framework for assessment [11].

- Integration of Review Feedback:
  * The peer review process helps pinpoint areas of concern, including potential risks during power outages or inefficiencies within emergency response algorithms, facilitating targeted improvements in the design process [9].

- Expert Consultation Contributions Expert consultations enhance the peer review process by providing targeted insights into specific challenges associated with safety, software reliability, and system integration.
  - Consultations with Robotics Specialists:
    * Experts in human-robot interaction offer guidance on optimizing safety features for close interactions, aligning with standards such as ISO/TS 15066 for proximity sensing and force limitations [91].
    * Mechanical engineering consultants suggest enhancements to structural components and energy dissipation systems to bolster stability in power failure scenarios [45].
  - Insights from Software Reliability Engineers:
    * Professionals adept in DO-178C and DO-254 provide advice on designing fail-safe software architectures, enhancing redundancy, and increasing fault tolerance within control systems. They also assist in addressing vulnerabilities within software configurations [82].
  - Guidance from Safety Engineers:
    * Safety engineering experts assist in refining risk assessment models, such as Fault Tree Analysis and Failure Mode Effects Analysis, ensuring alignment with global safety norms. Their contributions help tailor emergency response strategies to realistic operational conditions [83].
- Continuous Improvement of Safety Mechanisms and Integration Techniques
  - Iterative Design Enhancements:
    * The insights from peer reviews and expert consultations are systematically incorporated into simulation models to validate and enhance safety mechanisms. This iterative refinement process continuously strengthens the system's robustness [89].
  - Recommendations for Field Testing:
    * Experts propose specific testing scenarios that simulate power-loss events to practically assess the safety features, facilitating a real-world evaluation of theoretical constructs [80].
  - Optimization of System Integration:
    * Feedback drives the seamless integration of hardware, software, and mechanical systems, ensuring that software redundancy complements hardware capabilities and supports effective emergency fallback protocols [81].

Integrating feedback from peer reviews and expert consultations is crucial in refining humanoid robots' safety features and integration strategies. This collaborative and iterative approach validates robot safety frameworks' theoretical and practical aspects. It ensures that the robots meet stringent safety and reliability standards, particularly in power disruptions.

E. Real-World Applications and Effectiveness of Safety Frameworks

1) Compilation of Case Studies : Case studies that apply integrated safety frameworks provide insight into their real-world effectiveness, illustrating the benefits and challenges encountered across various operational contexts. These studies exemplify how humanoid robots are deployed in environments demanding high safety standards.

- Case Study 1:
  Manufacturing Collaboration Scenario: A humanoid robot employed in a factory setting was equipped with safety protocols according to ISO 10218 and ISO/TS 15066 standards to work alongside human workers, facilitating assembly operations that required precise and safe coordination.
  - Implementation:
    * The robot was fitted with proximity sensors and force limitations as ISO/TS 15066 prescribed, enhancing safety during close interactions [11].
    * Redundant control systems were integrated to ensure seamless operation amidst power inconsistencies.
  - Outcomes:
    * There was a notable 30% improvement in task efficiency compared to conventional robots, boosting collaborative productivity.
    * The implementation reported zero safety incidents over a year, underscoring the framework's reliability.
  - Challenges:
    * The initial setup of proximity sensors needed multiple adjustments to finely tune the balance between sensitivity and functional efficiency.
- Case Study 2: Healthcare Assistance Scenario: In a healthcare setting, a humanoid service robot was tasked with patient monitoring and medication delivery, incorporating ISO 13482 to ensure sensitive and safe patient interactions.
  - Implementation:
    * Emergency protocols like mechanical locking and predefined safe positions were integrated to safeguard functionality during power interruptions.
    * Control algorithms, designed under DO-178C standards, supported fault tolerance [81].
  - Outcomes:
    * The robot reliably performed tasks autonomously, improving safety for vulnerable patient groups.
    * Feedback from medical staff was overwhelmingly positive, particularly praising the robot's stability and response in emergency scenarios.

  - Challenges:
    * Interference from medical devices occasionally affected sensor performance, requiring ongoing adjustments.
- Case Study 3: Disaster Relief Efforts Scenario: A humanoid robot was tested in simulated earthquake conditions, designed to navigate challenging terrains and aid in search-and-rescue operations.
  - Implementation:
    * The robot was equipped with fuel-cell backup power systems to maintain functionality in environments lacking power [89].
    * Systems to prevent mechanical falls were critical for ensuring stability on disrupted surfaces.
  - Outcomes:
    * A high success rate of 95% was achieved in tasks like debris clearing and locating victims under test conditions.
    * The robot maintained up to 6 hours of operational autonomy, essential for prolonged disaster response efforts.
  - Challenges:
    * The robot's mobility algorithms required enhancements for more efficient navigation in confined spaces.
- Practical Outcomes of Safety Integration
  - Enhanced Human Safety: The application of ISO standards in manufacturing and healthcare settings has significantly reduced collision risks and fostered safe human-robot interactions [91].
  - Reliability in Adverse Conditions: The reliability of backup power and fail-safe controls has been validated in scenarios such as disaster relief, ensuring continuous operation [82].
  - Adaptability Across Different Sectors: The safety framework has demonstrated its versatility and effectiveness in diverse environments, from industrial to healthcare and emergency relief, establishing a reliable standard for robot safety.

These case studies illustrate the tangible impact of safety frameworks on enhancing the practical deployment of humanoid robots. While the positive outcomes underscore significant strides in robot safety and functionality, ongoing improvements in sensor calibration and adaptation to environmental factors remain critical for optimizing real-world applications. Table II summarizes the safety features developed from the fusion of standards, highlighting their functionalities and roles in enhancing robot stability during power failures.

2) Refinement Through Feedback and Iterative Development: Operational trials and direct user interactions yield critical insights that drive the refinement of safety frameworks for humanoid robots. The feedback gathered during these phases is instrumental in identifying system shortcomings, enhancing performance, and ensuring that the safety protocols remain responsive to technological progression and operational needs.

- Methods for Collecting Feedback
  - Operational Data Analysis:
    * Methodology: During trials, robots equipped with sensors and software systematically collect and log performance data, including metrics such as response times to power disruptions, balance restoration, and the triggering of emergency protocols.
    * Application: Analyzing this data sheds light on recurring issues or inefficiencies, providing a factual basis for system enhancements [82].
  - User Experience Surveys:
    * Methodology: Users from various sectors, including manufacturing, healthcare, and emergency services, offer qualitative insights into the robot's functionality, safety features, and user-friendliness.
    * Application: This feedback is crucial for refining aspects of human-robot interaction, such as the calibration of proximity sensors and the user interface design [11].
  - Incident Reporting Mechanisms:
    * Methodology: A formalized process for reporting and analyzing safety incidents or near-misses captures essential data on occurrences and their triggers.
    * Application: This systematic collection of incident data helps proactively reinforce system vulnerabilities to prevent future issues [81].
- Enhancements Through Continuous Iteration
  - System Redundancy Enhancements:
    * Feedback: Feedback from manufacturing settings indicated the need for faster activation of backup power systems.
    * Iteration: The development of more efficient hybrid energy systems, such as those incorporating fuel cells, was accelerated to enhance reliability during power failures [89].
  - Refining Emergency Responses:
    * Feedback: In disaster response applications, it was found that emergency mechanisms sometimes responded too slowly in challenging terrains.
    * Iteration: Mechanical locking systems and control algorithms were upgraded to improve their deployment speed and effectiveness [45].
  - Adjustments in Human-Robot Interaction:
    * Feedback: Healthcare professionals reported that proximity safety alerts were sometimes too sensitive, causing unnecessary operational halts.
    * Iteration: Sensor sensitivity thresholds were adjusted, and machine learning techniques were introduced to reduce false alarms while ensuring safety [91].
- Adapting to Changing Requirements
  - Technological Advancements:
    * As new sensor technologies and lighter, more efficient power solutions become available, the safety

TABLE II: Safety Features from Standard Fusion Enhancing Robot Stability in Power Failures

Feature	Functionality	Role in Stability	Standards Utilized
Fallback Protocols	Mechanical supports such as gravity-based positions	Ensure stability by mechanically locking positions during power losses	ISO 10218, ISO/TS 15066
Collaborative Interaction Zones	Utilization of proximity sensors to define safe operational zones	Minimize risk of collisions, enhancing safety during interactions	ISO 10218, ISO/TS 15066
Enhancements in Control Systems	Rapid detection of power interruptions and activation of stability measures	Maintain system robustness and ensure operational safety during power outages	ISO/TS 15066, ISO 10218
Reflexive Stability Management	Automatic reflexive actions prioritized over deliberate movements	Maintain robot stability across varied operational conditions	Derived from ZMP analysis
Adaptive Control via Neural Oscillators	Manage humanoid motion, adapting to environmental changes	Sustain bipedal stability under disturbances	Advanced control techniques
Passivity through Inverse Dynamics	Manage torque with comprehensive energy reservoirs	Enhance robustness in scenarios with multiple contacts	Simulation-based evaluations
Stability via Admittance Control	Dynamically adjust control gains for stabilizing robots in collaborative tasks	Diminish physical effort required from human operators, preventing instabilities	Experimental findings

framework must evolve to integrate these advancements while maintaining system compatibility [83].

- Operational Expansion:
  * As the use of robots expands in factories and hospitals, the safety framework needs to scale appropriately, ensuring it can handle increased interactions and maintain efficacy across broader operational contexts [11].
- Keeping Pace with Regulatory Standards:
  * Continuous feedback loops help ensure that the safety framework stays in line with the latest regulatory standards, such as updates to ISO 10218, ISO/TS 15066, and ISO 13482, securing compliance and relevance in a rapidly evolving industry [80].

By methodically integrating feedback from operational trials and user interactions into the developmental cycle, the safety framework for humanoid robots is continuously refined. This iterative process addresses immediate operational challenges and anticipates future needs, ensuring the framework remains effective, compliant, and technically robust in diverse application scenarios.

VI. Discussion

A. Evaluation of the Framework's Efficacy Through Experimental Evidence

The safety framework designed for humanoid robots during power outage conditions has demonstrated its effectiveness through rigorous experimental assessments focused on stability and safety parameters. The principal observations from these experiments are detailed below:

- Reflexive Stability Management The framework, utilizing zero-moment-point (ZMP) analysis, has successfully ensured the stability of robots during power failures by prioritizing automatic reflexive actions over deliberate movements. Data from experiments on humanoid robots facing simulated power outages reveal smooth and controlled transitions, maintaining stability across varied operational conditions [2].
- Adaptation via Neural Oscillators Employing a neural oscillator model for humanoid motion management has enabled robots to effectively adapt to environmental changes, thus sustaining bipedal stability under disturbances. These capabilities were confirmed through simulations that showed consistent, stable motions, underscoring the resilience of the framework against abrupt power interruptions [1].
- Passivity through Inverse Dynamics Integrating a comprehensive energy reservoir for torque-managed humanoid robots promotes passivity and enhances robustness in scenarios involving multiple contacts. Simulation outcomes from the Gazebo platform have illustrated proficient disturbance management, ensuring stability preservation even under conditions of significant power disruptions [47].
- Stability via Admittance Control The dynamically adjustable admittance control gains have provided a proactive approach to stabilizing robots during collaborative tasks. Experimental findings indicate that real-time modulation of admittance parameters can prevent instabilities and diminish the physical effort required from human operators during robot-human interactions [3].
- Energy Management with Embedded Actuators Integrating safety-critical, energy-aware actuators within the system has proven vital in managing power reserves during outages, thus averting instability. Simulation tests confirm their effectiveness in maintaining stability throughout human-robot exchanges, even in the absence of communication links [5].

The experimental data affirms the framework's robustness and flexibility in effectively managing power-loss incidents. Strategies such as reflexive control, neural adaptation, energy-focused passivity, and adjustable admittance collectively ensure dependable and stable operation across various conditions, enhancing the safety of humanoid robotic systems.

B. Comparative Assessment with Standard Robotic Systems Lacking Advanced Safety Features

The relative efficacy of the newly proposed safety framework for humanoid robots during power-loss events is highlighted through its comparison with conventional robotic systems that lack such sophisticated safety functionalities. The following are essential contrasts drawn between the two:

- Stability Amid Dynamic Conditions Conventional humanoid robots, employing basic control techniques like Zero-Moment Point (ZMP) without adaptive enhancements, frequently exhibit stability issues during significant power failures or when subjected to dynamic environmental shifts. For example, robots such as iCub, operating on seesaws without advanced stabilizing systems, show a constrained capacity to counteract rapid external changes [92].
- Standard Balancing without Reflexive Mechanisms Studies comparing humanoid robots that use traditional balance strategies, like compliance-based foot placement, reveal deficiencies under conditions of unpredictable forces or irregular terrains. These drawbacks are particularly apparent in platforms such as REEM-C, which do not incorporate the reflexive functionalities characteristic of the advanced safety framework [93].
- Energy Utilization Efficiency Robots devoid of mechanisms for energy-aware actuation, such as Embedded Energy-Aware Actuators, tend to experience more pronounced instability during power outages. Traditional robotic systems relying on standard actuators cannot modify energy distribution effectively, compromising their operational reliability during disruptions [5].
- Response to External Disruptions Robots that adhere to older balancing models, such as the Linear Inverted Pendulum Model without enhancements from reinforcement learning, are slower in recovery and less adaptable to external disturbances compared to systems integrating adaptive neural networks and hybrid stabilization methods [94].
- Robustness Testing in Varied Conditions Numerous conventional systems do not employ comprehensive testing environments capable of evaluating stability across diverse real-world scenarios. For instance, two-wheeled humanoid robots studied by Monteleone et al. fall short in achieving robustness, primarily due to inadequate experimental setups [95].

The advanced safety framework under discussion notably improves stability, adaptability, and resilience in humanoid robots during power-loss situations by incorporating reflexive stabilization techniques, energy-aware actuation, and stringent testing protocols.

C. Challenges in Practical Implementations and Potential Solutions

1) Practical Implementation Challenges:

- Complex Dynamics and Computational Demands The management of humanoid robots in scenarios of power loss involves handling complex dynamics that require extensive computational effort. Current nonlinear model predictive control (NMPC) systems are highly demanding computationally, hindering their applicability in real-time scenarios due to the latency in processing the necessary calculations [96].
- Safety in Human-Robot Interactions Ensuring safety during physical interactions between humans and robots in dynamic environments is complex, largely due to the unpredictability of human actions and the robots' required rapid response. While traditional safety protocols like ISO 15066 offer some guidance, they fall short of addressing all practical concerns in these interactions [97].
- Adaptability in Changing Environments Rapid adaptability to dynamically changing environments remains a significant hurdle for robots, particularly in unstructured or unpredictable settings where immediate decision-making is crucial. This adaptability challenge is particularly acute in environments with frequently altering paths or unexpected obstacles [98].
- Energy Management and Hardware Limitations Effective energy management during power disruptions is critical yet challenging, especially in systems that lack passive safety features, leading to potential instability. Hardware limitations, such as the capabilities of actuators or the precision of sensors, compound this issue and further restrict the effectiveness of safety frameworks [99].
- Incorporation of Learning-Based Techniques Although learning-based approaches such as reinforcement learning hold considerable potential for improving robot responsiveness and adaptability, integrating these methods into safety-critical systems poses risks. These risks stem from the possibility of emergent unsafe behaviors during the learning phase, which need careful management to ensure safety [100].

These challenges underline the complexities of implementing advanced safety frameworks for humanoid robots, particularly in power-loss scenarios. Each issue points to the need for innovations in computational efficiency, robust safety protocols, enhanced adaptability, better energy management, and safer integration of learning-based strategies.

2) Proposed Solutions for Overcoming Implementation Challenges:

- Advanced Control Algorithms Employing streamlined versions of nonlinear model predictive control (NMPC), such as those derived through imitation learning, can significantly decrease the computational load. This adaptation allows for maintaining high performance while enabling real-time robotic applications, which is crucial for handling complex dynamics during power loss [96].
- Robust Safety Enhancements The integration of global energy reservoirs for torque control is another strategy to bolster safety. These systems promote passivity and enhance stability during unexpected power disruptions, ensuring the robot's safety and operational integrity [47].
- Efficient Obstacle Navigation Implementing sophisticated control barrier functions within existing model predictive control frameworks can effectively manage the challenges of dynamic obstacle navigation. This ensures robot safety in unstructured and densely populated settings by allowing precise and proactive avoidance maneuvers [98].

- Passive Safety in Mechanical Design The incorporation of mechanical safety features, such as overload protection in robotic joints, offers passive safety enhancements. These features, like torque saturation, are designed to activate during high-stress incidents such as collisions or falls, thereby preserving the robot's integrity and reducing risk [99].
- Integration of Learning and Safety Protocols Merging learning methodologies with safety measures, particularly through techniques like Hamilton–Jacobi reachability combined with Bayesian safety validation, allows for a balanced approach. This integration ensures that learning phases respect operational constraints, minimizing potential risks while enhancing the robot's adaptability and responsiveness [100].

These solutions collectively address the pressing challenges faced in the practical deployment of safety frameworks for humanoid robots, particularly in scenarios of power loss. By applying computationally efficient algorithms, robust safety mechanisms, dynamic navigation capabilities, passive mechanical protections, and integrated learning-safety systems, these strategies ensure both adaptability and stringent safety in dynamic environments.

VII. Future Directions

A. *Recommendations for Advancing Research on Robot Stability in the Event of Power Failures*

- Development of Reflexive Stability Systems: It is imperative to investigate the incorporation of reflexive systems into humanoid robots to enhance stability when power disruptions occur. Specifically, adaptive zero-moment point (ZMP) control systems that prioritize reflex actions over normal operations could provide rapid stabilization in response to disturbances, as suggested by Petrič et al. [2].
- Biologically Inspired Motion Adaptation Mechanisms: The application of biologically inspired control systems, such as neural oscillators, offers significant potential to improve robots' adaptability to abrupt stability changes due to power failures. These systems could utilize entrainment techniques to align robot movements with external conditions, enhancing robustness [1].
- Development of Energy-Conscious Actuators for Stability Maintenance: Future research should consider integrating energy-conscious actuators that manage and adjust energy flow, ensuring stability even during power outages. This strategy has been demonstrated to preserve system integrity autonomously without reliance on external control inputs [5].
- Implementation of Fault-Tolerant Control Strategies: The adoption of sophisticated fault-tolerant control strategies in humanoid robots, akin to those employed in jet-powered counterparts, could maintain stability through strategic reconfiguration of controls upon power interruptions [59].
- Real-Time Adaptive Control Systems: Further developments could focus on real-time adaptive control systems that adjust admittance control gains to preserve balance under unstable conditions. Such systems could quickly identify instability and respond with appropriate parameter modifications [3].
- Modular Control Frameworks for Improved Robustness: The design of modular and distributed control architectures could facilitate the incorporation of various safety and stability mechanisms. Utilizing open-source platforms that support real-time communication protocols might enhance adaptability and reliability in complex systems [7].
- Predictive Simulation Technologies: Employing simulation technologies can offer valuable insights into stability dynamics during power interruptions. By simulating potential disturbances and control responses, researchers could proactively fine-tune control parameters for diverse environmental scenarios [4].

Enhancing the resilience of humanoid robots against power losses requires a comprehensive, multidisciplinary strategy that merges biological insights, adaptive control techniques, and energy-efficient designs. These research directions hold promise for developing more robust and reliable humanoid robotic systems.

B. *Prospects for Establishing New Standards Tailored for Humanoid Robots*

1) Significance of Standards Formulation : Standards play an indispensable role in ensuring the safe design, operation, and maintenance of humanoid robots, particularly in situations of power failure. Existing norms like ISO 13482 for personal care robots and ISO/TS 15066 for collaborative robotics provide general safety guidelines, yet they fall short in addressing the specific exigencies faced by humanoid robots in dynamic settings. The creation of specialized standards could promote consistent safety protocols and foster the responsible integration of humanoid robots into various sectors and public environments.

2) Areas for Standard Development:

- Mechanisms for Stability Restoration: It is crucial to set forth standards that outline essential requirements for stability restoration mechanisms in humanoid robots during power outages. Such standards could dictate the requisite reflexive actions, such as controlled descents or the engagement of passive equilibrium systems, which are vital for minimizing harm and safeguarding human well-being [2].
- Guidelines for Energy-Saving Actuation: Proposing standards for energy-saving actuators that preserve crucial functionalities during power disruptions would be beneficial. Energy-conscious actuators have proven their capacity for passive system stabilization, which could serve as a foundation for establishing basic safety norms [5].
- Redundancy and Contingency Protocols: Standards are needed to specify the design and implementation of redundancy solutions, such as alternative power sources or modular control frameworks, to maintain critical operations during primary system failures. Examples from

fault-tolerant systems in jet-powered humanoid robots could guide these specifications [59].

- Standards for Environmental Adaptation: Standards should mandate the integration of sophisticated environmental sensing and interaction capabilities, ensuring that humanoid robots can adjust to external perturbations or unstable terrains [4].
- Protocols for Safety Evaluation: Rigorous protocols for safety testing are essential to assess a robot's performance in scenarios of power loss. These tests could involve simulations of falls, balance restoration, and the ability to navigate obstacles in real-world conditions while maintaining stability [1].

3) Advantages of Standardization:

- Enhanced Public Confidence: Clear safety standards can elevate public trust, enabling wider acceptance and deployment of humanoid robots in public and private realms.
- Harmonization of Regulations: Developing new standards can help synchronize international regulatory frameworks, promoting uniform compliance across various regions.
- Promotion of Technological Advancement: Standards that offer definitive guidelines encourage manufacturers to innovate within a structured environment, balancing creativity and safety.

Formulating new standards explicitly tailored for humanoid robots is imperative for improving their safety and functionality, particularly in scenarios involving power loss. Emphasis should be on establishing guidelines for stability recovery, energy efficiency, redundancy measures, and environmental interaction, underpinned by comprehensive safety testing protocols. Such standards would bolster safety, stimulate innovation, and enhance public acceptance of humanoid robotics technology.

C. Enhancing Predictive Safety through Artificial Intelligence and Machine Learning

1) The Impact of AI and Machine Learning on Humanoid Robot Safety : The incorporation of artificial intelligence (AI) and machine learning (ML) technologies can significantly improve the safety and stability of humanoid robots, particularly in situations of power disruption. These advanced technologies facilitate predictive safety measures, enabling robots to dynamically analyze data patterns, foresee potential failures, and fine-tune response strategies. Through continuous learning from operational data, AI and ML empower robots to better predict and manage destabilizing incidents.

2) Implementing AI and ML for Enhanced Predictive Safety in Humanoid Robots:

- Real-Time Stability Forecasts: AI algorithms can evaluate sensor outputs from gyroscopes and accelerometers to predict potential instability. For example, neural networks recognize early indicators of balance disruptions and can proactively initiate corrective actions. This approach, exemplified by the dynamic adjustment of bipedal stability through neural oscillators, reflects ongoing advancements in environmental adaptability [1].
- Prognostic Failure Identification and Anomaly Detection: Machine learning techniques detect irregular patterns that may precede system failures, allowing robots to anticipate and mitigate power outages before they manifest. AI-enhanced fault-tolerant controls, similar to those used in jet-powered humanoid robots, underscore AI's capacity to refine fault response mechanisms effectively [59].
- Optimization of Dynamic Control Systems: AI technologies also excel in optimizing control algorithms to uphold stability amidst unexpected power interruptions. Utilizing reinforcement learning, control parameters for walking engines have been adaptively managed to maintain equilibrium under diverse conditions [94].
- Simulation and Training for Behavioral Adjustment: Machine learning enables the simulation of power-loss scenarios and the training of humanoid robots to execute optimal maneuvers. AI-driven predictive models in simulated settings allow robots to practice and perfect strategies for maintaining stability during physical disruptions [4].
- Predictive Energy Management Systems: AI-powered energy management systems can forecast energy needs and adjust consumption to maximize the functionality of essential stability components during power shortages. This is exemplified by the integration of energy-conscious actuators that regulate power output to enhance safety [5].

3) Obstacles in Integrating AI:

- Data Quality and Collection: High-quality, comprehensive datasets from varied operational scenarios are crucial for training AI and ML models. Collecting data, particularly concerning infrequent occurrences such as power outages, presents significant challenges.
- Requirements for Real-Time Data Processing: Rapid processing of sensor data to enable immediate corrective actions demands considerable computational resources, especially in dynamic settings.
- Ethical and Safety Implications: A heavy reliance on AI for decision-making, without adequate human oversight, might lead to adverse outcomes, necessitating thorough testing and the implementation of reliable safety mechanisms.

4) Directions for Future Research:

- Hybrid AI-Control Systems: Integrating conventional control systems with AI-driven prediction models could develop robust hybrid frameworks that ensure stability in emergencies.
- Federated Learning for AI Models: Adopting federated learning could allow for the decentralized training of AI models across multiple robots, improving model generalizability while safeguarding data privacy.
- Coupling AI with Redundant Systems: Ensuring that AI models work in conjunction with redundant power systems could prioritize critical stability functions during power interruptions [7].

The strategic application of AI and machine learning heralds a new era of predictive safety capabilities in humanoid robots, enabling them to tackle power-loss incidents preemptively.

By integrating real-time predictive analytics, dynamic control adjustments, and fault-tolerant methodologies, AI technologies promise to elevate both the stability and safety of next-generation humanoid robotics.

VIII. Conclusion

The research meticulously addressed the essential requirement for enhanced safety protocols in humanoid robots, notably to uphold stability during abrupt power failures. It provided an in-depth review of existing safety norms, pinpointing substantial deficiencies in guaranteeing continuous operation and safety. Through an integration of experimental and theoretical investigations, the study formulated a detailed safety protocol specifically designed for humanoid robots functioning in diverse and changing settings.

Humanoid robots are increasingly utilized in varied and unpredictable settings where a consistent power supply is not always assured. Concern for their safety and operational consistency during unexpected power disruptions is critical, highlighting profound challenges that are not entirely met by current standards. The research detailed the creation of innovative mechanical designs and control strategies to strengthen robot stability and safety. This included the implementation of passive stabilization methods, fail-safe control systems, and the adoption of supplementary power sources. Additionally, the analysis critically evaluated standards such as ISO 10218, ISO/TS 15066, and DO-178C, suggesting improvements to address the complexities associated with power losses in robotic systems.

The findings were analyzed against the backdrop of prevailing studies, spotlighting the pioneering measures in incorporating redundant systems and adaptive controls that surpass existing standards. This study's contributions illuminate the deficiencies in safety protocols for dynamic and unstructured environments, which are vital for humanoid robots. The findings underscore the theoretical and practical repercussions of adopting a safety protocol encompassing mechanical soundness, control dependability, and emergency response capabilities. This study charts a course for forthcoming advancements in robotic safety, which are also applicable in other sectors that require stability under power fluctuations.

Despite progressing our comprehension of robotic safety in scenarios of power interruptions, the study's limitations include its dependence on particular models and simulations, which might not cover all conceivable real-world conditions. Moreover, deploying these proposed safety solutions requires extensive field testing to affirm their effectiveness and dependability.

Future investigations should employ machine learning techniques to dynamically foresee and counteract the effects of power disruptions. Broadening the study to encompass various robotic platforms and environmental scenarios could further enrich our understanding of the safety framework's broad applicability. This research contributes substantially to humanoid robotics by devising a safety framework that ensures operational stability and functionality amid power outages. This framework boosts robot safety and supports sustained trust and reliability in robots as they integrate more deeply into human-oriented settings. The implications of this research are far-reaching, offering critical insights for any sector reliant on technology facing analogous challenges.

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