

Dynamic Interactions and Predictive Insights: Revolutionizing Robotics with Piezoelectric Technology

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Abstract: *Piezoelectric sensors have emerged as a pivotal innovation in robotics, propelling advances in motion-sensing precision and encouraging the creation of adaptive, responsive robotic systems. These sensors, which transform mechanical stress into electrical impulses, allow for reliable detection of forces, vibrations, and pressures, making them vital in dynamic situations. This review explores how piezoelectric sensors improve robotic precision and responsiveness, allowing for seamless interaction with humans and other systems. The capacity to continually measure vibrations, accelerations, and strain is critical for machine predictive maintenance and wearable motion tracking. This review emphasized the revolutionary importance of piezoelectric sensors in defining the future of robotics and sensor-based technology.*

Keywords: Piezoelectric sensors, motion-sensing, robotics

I. INTRODUCTION

Over the past few years, robotics has seen a significant surge in development, primarily due to the escalating demand for intelligent, responsive, and adaptive systems across various sectors. Intelligent robots have been incorporated into multiple sectors beyond traditional industrial settings, including underwater exploration, medical care, and services, among others [1,2]. The integration of AI and machine learning techniques into robotics will facilitate advances in human-robot collaboration. Robots possess the capability to comprehend and adjust to human conduct, thereby enhancing their safety and the ease with which they can be used alongside humans. A robot's manipulative capabilities in any given area are largely reliant on the dynamic performance of its internal propulsion system. The internal drive system's ecological effects vary according to its design, energy efficiency, and power source. This concept involves the development of robots capable of adapting, enhancing their abilities, and acquiring knowledge through interactions with their surroundings, assignments, and people. Efficient robotic systems rely on the management and conversion of electrical power, such as during a robot's execution of a combination of high-energy and low-energy tasks, and learning-based control enables the dynamic allocation of energy resources [3]. Motion detection technology is a fundamental component in robotics, allowing robots to sense and react to physical movements occurring around them. As robots are increasingly incorporated into dynamic environments, from factory floors to personal support services, precise motion detection and interpretation are essential. At the core of this capability are motion sensors that capture real-time transformations in the position, velocity, and orientation of objects, including the robot itself. These sensors enable robots to navigate, interact with their surroundings, and even predict changes in the environment, thereby boosting their autonomy and adaptability [4]. Piezoelectric materials are promising candidates for efficient, versatile robotic systems and for motion sensing. Piezoelectric sensors are devices that exploit the piezoelectric effect, a physical phenomenon whereby certain materials produce an electric charge in response to mechanical stress. This principle stems from the inherent structures of piezoelectric materials like quartz and ceramics, where mechanical strain leads to the movement of electric dipoles, resulting in a quantifiable electrical signal. These highly sensitive sensors can accurately measure changes in pressure, force, vibration, and acceleration. The capacity to convert mechanical energy



into electrical energy without the need for external power sources makes these systems essential in applications requiring dynamic measurements, such as robotics, medical equipment, and industrial monitoring systems [5]. The operation of piezoelectric sensors is based on the inherent characteristics of piezoelectric materials. The deformation of a piezoelectric material through compression, tension, or shear causes a disruption to its internal charge distribution, leading to the creation of an electrical potential. The electrical charge generated is directly related to the mechanical stress applied, enabling precise measurement of force, pressure, or vibration. The electrical charge is subsequently gathered by electrodes connected to the material, transformed into a quantifiable signal, and analysed by the system. Unlike other sensor types, piezoelectric sensors don't need an external power source for the sensing process itself, as they produce their own electrical output in response to mechanical stimuli. Their efficiency is enhanced by this energy-harvesting characteristic, which also decreases the need for intricate power management systems [6].

Real-time information from piezoelectric sensors is crucial in determining the forces and pressures that various robotic components, including joints, actuators, and grippers, encounter. Piezoelectric sensors allow robots to execute sensitive operations with great precision by accurately gauging these mechanical forces, such as grasping, manipulation, and mobility. Moreover, these sensors enable the detection of vibrations, a crucial factor in pinpointing potential flaws or problems within the robot's framework or surroundings, as cited by various sources. A major advantage of piezoelectric sensors in robotics is their capacity to offer anticipatory knowledge about system functioning. By regularly tracking dynamic forces and vibrations, piezoelectric sensors can aid in predictive maintenance and boost robotic efficiency. By examining the patterns of strain or stress on different components, robots can predict wear and tear, thus avoiding expensive repairs and extending their lifespan. Piezoelectric technology in motion sensing enables robots to adjust their movements in real time, thereby delivering enhanced responsiveness and adaptability, crucial for tasks in unpredictable or complex settings [7]. As robotics continues to advance, piezoelectric sensors are set to become more integral in developing the next generation of intelligent systems. A unique blend of sensitivity, versatility, and efficiency allows robots to not only detect their environment but also forecast and adjust to alterations, establishing a basis for more self-governing, flexible, and streamlined robotic systems. This integration of piezoelectric technology has the potential to redefine the limits of robotics and motion detection, enabling the creation of more intelligent and capable robots across various applications, including industrial automation, healthcare, and beyond [8,9]. This review examines the function of piezoelectric sensors in enhancing dynamic interaction and providing predictive insights within robotic systems. Our goal is to gain a thorough understanding of piezoelectric technology's impact, by studying its underlying principles, importance, and capacity for innovation, which could significantly transform the robotics industry.

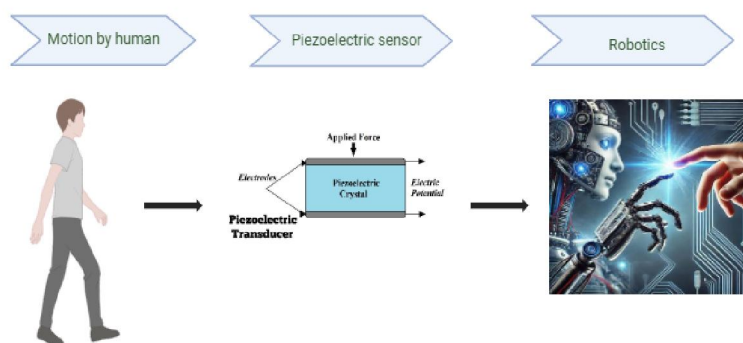


Figure 1: Schematic representation of Piezoelectric sensors integrated into robotic systems for motion sensing.

II. PIEZOELECTRICITY

Piezoelectricity, a phenomenon whereby certain materials generate electric charges upon experiencing mechanical stress, has revolutionized several fields of science and engineering since its discovery in 1880 by Pierre and Jacques Curie [10]. This electromechanical coupling effect, governed by the principles of symmetry breaking in crystalline



structures, arises from the displacement of charged ions within non-centrosymmetric lattices. Materials such as quartz, Rochelle salt, and certain ceramics initially dominated piezoelectric research and applications [10, 11]. However, advancements in material science have led to the development of more sophisticated piezoelectric materials, including lead zirconate titanate (PZT), polyvinylidene fluoride (PVDF), and various doped composites [12,13]. These materials exhibit enhanced piezoelectric coefficients and tailored electromechanical properties, making them indispensable in modern applications. Historically, piezoelectricity found its initial applications in sonar systems during World War I, where quartz crystals enabled underwater acoustic detection [12]. Subsequently, the development of synthetic piezoelectric ceramics like PZT in the mid-20th century catalyzed their use in actuators, sensors, and transducers [11, 14]. These ceramics, characterized by high dielectric constants and strong piezoelectric responses, have been employed in diverse fields, ranging from medical ultrasound imaging to industrial non-destructive testing [15]. Over time, research has transitioned from rigid materials to flexible piezoelectric polymers and nanocomposites, which are lightweight and conformable, expanding the scope of piezoelectric devices into wearable electronics and bio-integrated systems [16, 17].

Flexible piezoelectric devices, as discussed in Liu et al. (2022) [], have become pivotal in the development of human-machine interfaces (HMIs). By utilizing materials such as PVDF and its copolymers, researchers have achieved enhanced stretchability and sensing capabilities [16]. These devices are now employed in applications like gesture recognition, health monitoring, and robotic control. For instance, piezoelectric sensors integrated into gloves can convert finger movements into electrical signals, enabling real-time control of robotic hands [18]. Additionally, advances in two-dimensional materials like tin disulfide (SnS_2) nanosheets have introduced ultra-thin, high-sensitivity sensors capable of detecting subtle mechanical stimuli [16]. These innovations, paired with machine learning algorithms, have paved the way for intelligent and adaptive HMI systems [17].

In the realm of robotics, piezoelectric actuators have facilitated the miniaturization and enhancement of robotic systems. As outlined by Jing Li et al. (2023) [14], miniature piezoelectric robots (MPRs) leverage the inverse piezoelectric effect to achieve precise and agile movements. These robots are classified based on their operational environments, structural designs, and actuation principles. For example, terrestrial MPRs employ piezoelectric stacks or patch beams to drive locomotion through friction-based mechanisms, while aquatic MPRs utilize flexible actuators mimicking fish tails for propulsion [14, 6]. Recent developments include hybrid robots capable of transitioning between multiple environments, such as land and water. The integration of advanced piezoelectric materials like doped PMN-PT films has further enhanced the performance of these robots by improving their output force, resolution, and durability [13, 15].

The utilization of piezoelectricity in energy harvesting is another burgeoning area of research. By converting ambient mechanical vibrations into electrical energy, piezoelectric harvesters provide sustainable power solutions for low-energy devices [16, 17]. Applications range from powering IoT sensors in smart homes to self-sustaining wearable electronics. For instance, piezoelectric pavement blocks can generate energy from foot traffic, which can be used to illuminate walkways or power environmental sensors [18]. Similarly, piezoelectric materials embedded in clothing can harvest energy from human motion, powering devices such as fitness trackers or medical monitors [16]. The development of novel piezoelectric nanostructures, such as nanowires and nanofibers, has significantly increased the efficiency of energy harvesters by enhancing their surface area and sensitivity [16,17]. In healthcare, piezoelectric materials have found extensive applications in diagnostics, therapeutics, and rehabilitation [15].

Ultrasonic transducers, which rely on piezoelectric ceramics, are integral to medical imaging techniques like ultrasound. These transducers convert electrical signals into high-frequency sound waves, which penetrate biological tissues to create diagnostic images [15, 16]. Additionally, piezoelectric devices are used in wearable sensors for continuous health monitoring, such as detecting heart rate, respiration, and joint movements. Therapeutic applications include acoustic stimulation for tissue repair and piezoelectric actuators for controlled drug delivery [18]. The biocompatibility and tunability of modern piezoelectric materials make them ideal candidates for implantable medical devices, such as cochlear implants and cardiac pacemakers [16, 17]. The progression of piezoelectric materials has been closely linked to advancements in fabrication techniques and computational modeling. Techniques such as sol-gel processing, electrospinning, and additive manufacturing have enabled the creation of complex piezoelectric structures



with precise control over their properties [17,18]. For example, piezoelectric nanocomposites can now be engineered with hierarchical architectures to optimize their mechanical flexibility and electrical output [8]. Computational tools, including density functional theory and finite element analysis, have provided insights into the atomic-scale mechanisms of piezoelectricity and guided the design of new materials with enhanced performance [17, 18].

Despite these advancements, several challenges remain in the field of piezoelectric research. One significant issue is the environmental impact of lead-based ceramics, such as PZT [13]. The toxicity of lead has prompted efforts to develop lead-free alternatives, such as barium titanate (BaTiO_3) and potassium sodium niobate (KNN) [13]. While these materials exhibit promising piezoelectric properties, their performance often falls short of lead-based counterparts. Another challenge is the scalability of manufacturing processes for flexible piezoelectric devices, which often require specialized equipment and materials [16]. Furthermore, the integration of piezoelectric systems into existing electronic platforms necessitates advances in circuit design and energy management [17]. Looking ahead, the future of piezoelectricity lies in the convergence of material science, nanotechnology, and artificial intelligence [16]. Smart piezoelectric systems, capable of self-adapting to their environments and autonomously optimizing their performance, represent a promising direction for research [18]. For instance, integrating piezoelectric sensors with neural networks can enable real-time data processing and decision-making in robotics and healthcare. Additionally, the exploration of hybrid piezoelectric materials, which combine organic and inorganic components, may yield unprecedented levels of flexibility, sensitivity, and durability [19].

III. DYNAMIC INTERACTION IN ROBOTICS

Robotics involves ongoing interactions between a robot and its surroundings, where forces and movements are constantly exchanged. This process depends on sophisticated sensors, actuators, and control algorithms that enable robots to adjust to shifting circumstances in real-time. During the assembly or object manipulation process, force sensors track the impact, whereas control systems make precise adjustments to maintain stability and efficiency. The integration of machine learning and artificial intelligence improves these interactions by allowing robots to predict and adapt to complex situations, like human-robot collaboration or navigating unpredictable environments.

The importance of dynamic interactions stems from their capacity to enhance robot functionality, security, and adaptability in various sectors. In the manufacturing industry, robots equipped with dynamic interaction capabilities can manage fragile materials with accuracy or react to unforeseen disturbances without sustaining damage. In the healthcare field, these interactions allow robotic prosthetics and surgical robots to function with a level of dexterity similar to that of humans. Furthermore, dynamic interactions enable safe navigation in unpredictable settings for autonomous vehicles and drones. Dynamic interactions play a crucial role in bridging the gap between traditional programming methods and adaptive behaviour, thereby facilitating robotics advancements in areas such as increased autonomy, improved efficiency, and smoother integration into environments centered around human needs.

3.1 Case Study 1: Piezoelectric in Soft robots

The field of soft robotics has developed as a pioneering area focused on creating robots with properties of compliance, flexibility, and adaptability comparable to those of living organisms. At the heart of this field lies the incorporation of piezoelectric sensors, which are essential for dynamic interactions with the environment. These sensors utilise the piezoelectric effect - the property of specific materials to produce an electrical charge as a result of mechanical strain - to measure force, pressure, and displacement. Their high sensitivity, lightweight construction, and capacity for integration into flexible substrates make them particularly well-suited for applications in soft robotics. Piezoelectric sensors have transformed the field of soft robotics by offering highly sensitive feedback on force, pressure, and deformation, thereby allowing for real-time adaptability and precision in robotic operations. Robots designed to replicate biological systems require flexible and pliable materials to accomplish intricate operations within unpredictable settings. Piezoelectric materials such as polyvinylidene fluoride (PVDF) and its copolymers, as well as advanced composite materials like PVDF-TrFE and hybrid organic-inorganic nanostructures, are commonly used in these sensors. PVDF is notably advantageous due to its high piezoelectric coefficients, flexibility, and biocompatibility, which make it suitable for integration into soft robotic actuators and grippers [20].



These sensors are integrated into soft robots to track deformation, identify tactile stimuli, and quantify strain. Robotic grippers are frequently employed in precision agriculture and medical fields, where sensor technology assists in identifying the precise force necessary to handle fragile items like fruits or sensitive medical equipment without causing them harm. Soft robots equipped with piezoelectric sensors can engage in safe interactions with humans, opening possibilities for wearable technology and assistive tools, including robotic hand devices designed for rehabilitation purposes. Piezoelectric materials also offer a benefit in energy harvesting, enabling sensors to power themselves during dynamic interactions [20].

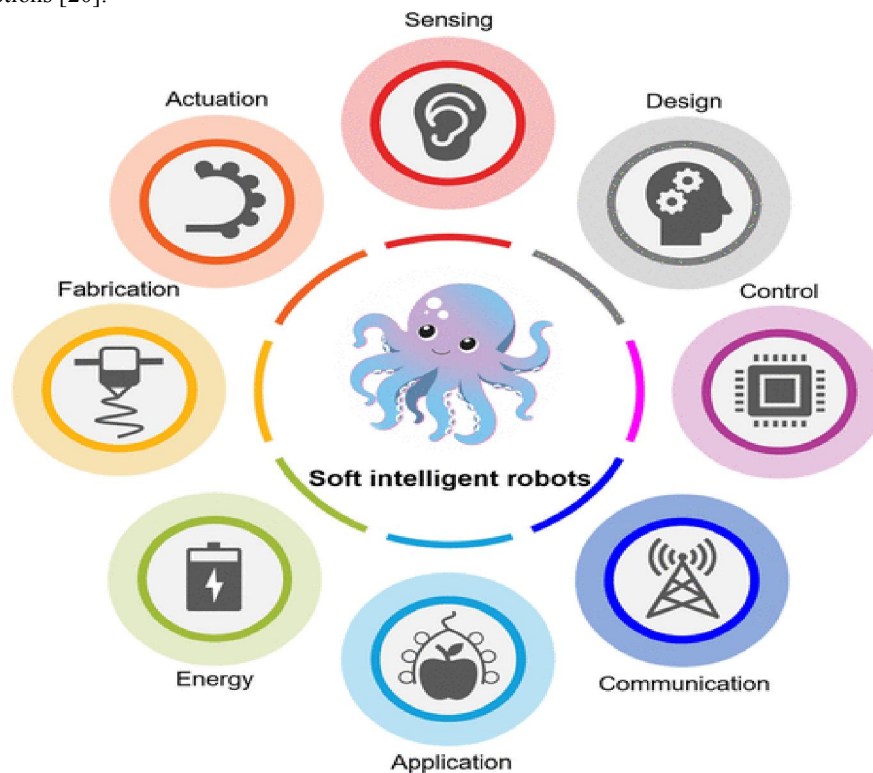


Figure 2: Key components and factors to consider in the construction of a smart soft robot. The diagram illustrates the crucial elements necessary for building a sophisticated soft robot, comprising actuation, sensing, and energy provisioning, along with the electronics required for control and connectivity. Furthermore, key factors, including fabrication techniques, design, control protocols, and application specifics, are also discussed [20].

3.2 Case Study 2: Piezoelectric in HRI (Human -Robot Interaction)

Advances in Human-Robot Interaction have been made possible by the integration of piezoelectric sensors, leading to the creation of flexible, responsive, and efficient interfaces. A notable example is the study "A Flexible Piezoresistive/Self-Capacitive Hybrid Force and Proximity Sensor to Interface Collaborative Robots," which showcases a new sensor designed to improve collaborative robotics technology. This novel sensor integrates piezoresistive and self-capacitive sensing technologies to measure both force and distance, thereby overcoming the drawbacks associated with conventional robotic sensors. Conventional sensors typically monitor a single property, are expensive to produce, and lack physical versatility, rendering them less suitable for a wide range of robotic configurations. In contrast, this hybrid sensor boasts mechanical flexibility, cost-effectiveness, and simplicity of application, even on intricate robot surfaces. The manufacturing process involves the production of a thin sensor, measuring 1 mm in thickness, which can adapt to various surfaces. This sensor's flexibility is showcased through its use in two different settings: using touch commands to guide a robot manually and preventing human-robot collisions through proximity detection. In the hand-guiding scenario, the sensor facilitates straightforward control of the robot by identifying touch inputs, allowing for



smooth human intervention. For collision avoidance, the sensor uses proximity detection to guarantee safety by detecting potential obstacles before they are reached [21].

Experimental trials were conducted to determine the sensor's response to both force and proximity. The outcomes demonstrated the sensor's accuracy, reduced drift, and repeatability, thereby confirming its suitability for use in various fields. The incorporation of such sensors into collaborative robots improves their capacity to interact safely and effectively with humans, thereby facilitating the development of more intuitive and responsive human-robot interaction systems. This research showcases the potential of piezoresistive and self-capacitive sensing methods to overcome the shortcomings of conventional sensors, thereby enabling more adaptable and efficient human-robot interfaces. The creation of flexible and multifunctional sensors is vital for the advancement of collaborative robotics, guaranteeing both safety and efficacy in human-robot interactions [21].

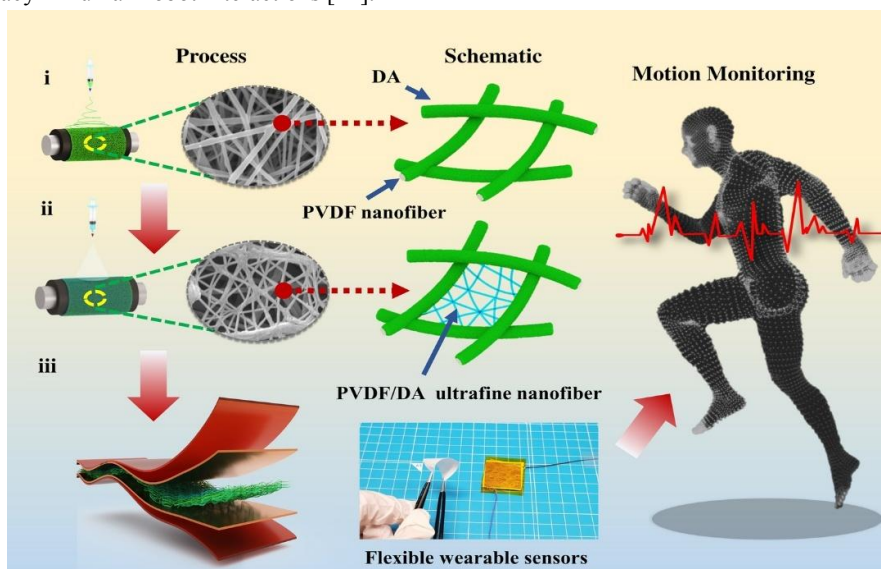


Figure 3: Schematic of the fabrication of composite nanofiber piezoelectric sensor with hierarchical structure [21].

Case Study 3: Piezoelectric in Mesoscale Mobile Robots:

Advanced mesoscale mobile robots are being developed primarily using piezoelectric materials, which have a distinctive property of converting mechanical energy into electrical energy and also vice versa. PZT is the most widely used of these materials due to its high piezoelectric coefficient, high energy conversion rate, and long-lasting nature. Materials like barium titanate and polyvinylidene fluoride (PVDF) have gained acceptance particularly for applications that need flexibility or biocompatibility. PZT is mainly used in applications needing robust actuation and precise motion control, whereas PVDF is preferred for its lightweight and flexible nature, making it suitable for robots interacting with delicate environments or requiring lightweight designs. The main focus of integrating piezoelectric materials into small-scale mobile robots is on actuation, sensing, and energy harvesting. Precise, small-scale motions are achieved through the use of piezoelectric materials, which expand and contract in response to applied electrical fields. This property facilitates the creation of micromechanical structures, including walking legs, crawling mechanisms, or swimming fins, thereby enabling robots to replicate biological movements. Piezoelectric actuators can propel inchworm-like or caterpillar-like motion, which results from sequential expansion and contraction leading to forward movement. These actuators offer several benefits for mesoscale robots, primarily due to their compact size, high power-to-weight ratio, and capacity to function in confined spaces without the need for large motors or complex gearing systems [22].

Piezoelectric materials play a crucial role in sensing applications, particularly in detecting environmental interactions like force, pressure, or vibration. Inside the robot, piezoelectric sensors are embedded within its framework, giving it real-time readings on external forces, allowing it to modify its movement or stance to preserve stability and optimise its



performance. This capability is particularly important for applications needing exact environmental interactions, including robots moving across rough terrain or carrying out tasks in sensitive settings, such as medical procedures or precision assembly lines. A piezoelectric sensor integrated into a robot's legs can identify surface imperfections and modify the leg's placement and pressure, thereby guaranteeing stable movement. Piezoelectric materials find another significant application in mesoscale mobile robots as energy harvesting systems. These materials are capable of capturing ambient vibrations, mechanical stress, or movement and converting them into electrical energy, which is then used to power the robot's systems. This feature is especially advantageous for robots working in distant or hard-to-reach areas where replacing or recharging the battery is not feasible. A mesoscale robot equipped with piezoelectric energy harvesters can carry out autonomous tasks in environmental monitoring missions, gathering data for prolonged periods without needing to draw power from external sources. The design principles of mesoscale mobile robots that utilize piezoelectric materials typically emphasize efficiency, flexibility in response to changing conditions, and the ability to perform multiple functions simultaneously. The referenced study highlights a notable innovation that includes a sliding amplification system which boosts the force produced by piezoelectric actuators. This mechanism utilises a combination of leverage and mechanical transmission systems to amplify the small displacements characteristic of piezoelectric materials, converting them into larger, more efficient motions appropriate for mesoscale locomotion. This method enables robots to attain high mobility and flexibility without compromising efficiency or size. These designs allow a robot to navigate over uneven terrain, ascend slopes, or move through tight spaces, making them well-suited for uses such as search-and-rescue operations, where adaptability and dependability are essential.

The adaptability of these robots is also reflected in their overall structural configuration. Numerous mesoscale robots employ soft or pliable components in conjunction with piezoelectric materials, enabling them to adapt to their environment or interact with delicate objects. In medical contexts, robots must be able to safely manoeuvre through the human body and handle sensitive tissues to avoid causing any damage. A surgical robot on a mesoscale could utilise piezoelectric actuators and sensors to deliver precise, controlled movements for minimally invasive operations, with real-time sensor feedback providing safety and accuracy. Environmental monitoring is a particularly important application area [22]. Mobile robots with piezoelectric systems can traverse complex terrain, including forests, deserts, and underwater settings, to gather data on temperature, humidity, pollutants, and other environmental factors. Continuous feedback from the piezoelectric sensors allows the robot to adjust its movement and maintain operational efficiency in its interactions with the environment. Piezoelectric materials enable robots to maintain themselves in distant locations for longer durations, thereby minimising the requirement for human involvement. In manufacturing environments, miniature robots equipped with piezoelectric movement and detection capabilities are employed in activities like precision assembly, quality control checks, and goods movement. Their ability to accurately control movement and react to external forces makes them well-suited for tasks such as assembling small parts, examining delicate materials, or manipulating objects in confined areas. A mesoscale robot equipped with piezoelectric grippers can accurately handle small electronic components during production, guaranteeing precision and uniformity without compromising the components' integrity. These applications are complemented by piezoelectric materials, which also enhance the durability and resilience of mesoscale mobile robots. Piezoelectric components can mitigate the consequences of mechanical vibrations and shocks by utilising their inherent damping properties, thereby safeguarding delicate components and enhancing the robot's longevity. This capability is especially significant for robots functioning in high-impact settings, including construction areas and disaster regions. Overall, the integration of piezoelectric materials into mesoscale mobile robots has revolutionized their design, functionality, and application potential. By combining actuation, sensing, and energy-harvesting capabilities in a single material system, piezoelectric materials enable robots to achieve high levels of autonomy, efficiency, and adaptability. This multifunctionality is especially important for mesoscale robots, where size and weight constraints necessitate compact, efficient designs. As research continues to advance, the development of new piezoelectric materials with enhanced properties, such as higher sensitivity, greater flexibility, or improved biocompatibility, will further expand the capabilities and applications of mesoscale mobile robots [22].



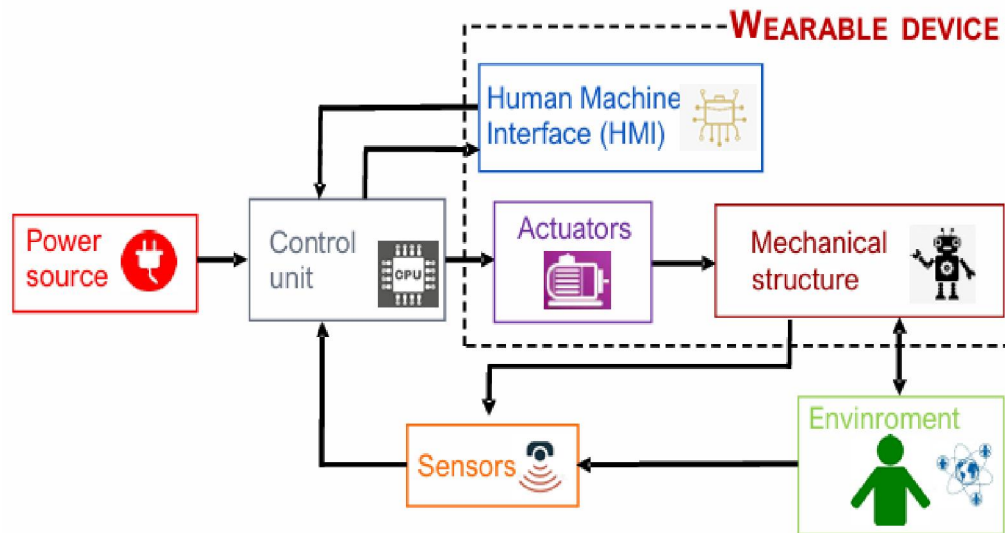


Figure 5: General architecture of a robotic exoskeleton. Actuators and sensors form the core components of the exoskeleton system, with actuators driving movement and sensors enabling seamless interaction with the user and the surrounding environment. The selection of actuator and sensor technologies plays a crucial role in determining the overall functionality, responsiveness, and performance of the device, often requiring careful integration to achieve optimal synergy [23].

IV. FUTURE TRENDS OF PIEZOELECTRIC TECHNOLOGY IN ROBOTICS

Significant advancements in robotics are expected to stem from the integration of piezoelectric sensors, which will be driven by improvements in materials science, artificial intelligence, and a growing need for collaborative efforts between humans and robots. Current and future advancements encompass the creation of flexible, biocompatible piezoelectric materials, which facilitate smooth integration with wearable robots and exoskeletons for medical care and physical therapy. The advent of self-powered piezoelectric systems will obviate the necessity for external power sources, thus enabling more energy-efficient and autonomous robots. Improvements in machine learning and data analysis will boost the predictive capabilities of piezoelectric sensors, allowing robots to predict and adjust to changing surroundings with higher accuracy. Miniaturization and integration of piezoelectric sensors within mesoscale and soft robots will also broaden their uses in sectors like medical diagnostics, search and rescue operations, and agriculture. The combination of piezoelectric technology with advancing techniques such as 3D printing and nanotechnology is anticipated to reconfigure sensor designs, thereby enabling new opportunities for robotics in precision-oriented tasks and human-machine communication.

V. CONCLUSION

Piezoelectric technology has proven transformative in advancing the design and functionality of robotic systems, bridging the gap between static automation and dynamic adaptability. By harnessing the unique properties of piezoelectric materials to sense, actuate, and harvest energy, this technology has enabled the development of intelligent and efficient robots capable of operating in complex and unpredictable environments. The seamless integration of piezoelectric sensors into robotics has revolutionized areas such as human-robot interaction, predictive maintenance, and autonomous operation by enhancing real-time responsiveness, precision, and energy efficiency.

Moreover, advancements in flexible and nanostructured piezoelectric materials have paved the way for innovative applications, including soft robotics, mesoscale robots, and wearable exoskeletons. These innovations address critical challenges in motion sensing, force measurement, and energy management, driving forward capabilities in industrial



automation, healthcare, and environmental monitoring. The concurrent evolution of materials science, AI, and nanotechnology holds immense promise for the next generation of robotics, offering unprecedented possibilities in energy-efficient, autonomous, and adaptive systems.

Future research must continue to tackle existing challenges, such as environmental concerns related to lead-based piezoelectric materials and the scalability of flexible device manufacturing. Collaborative efforts in developing lead-free materials, optimizing energy management systems, and integrating machine learning into sensor-based robotics will be instrumental in unlocking the full potential of piezoelectric technology. By doing so, piezoelectricity is poised to remain a cornerstone of innovation in robotics, enabling advancements that will redefine interactions between humans, machines, and their environments.

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