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Original Article

Smart Actuator Systems for Precision Robotic Applications

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ABSTRACT

Smart actuator systems are vital to precision robotics, enabling enhanced control, adaptability, and performance in complex environments. Prior to 2018, major advancements in actuator technologies—such as piezoelectric, shape memory alloy (SMA), electroactive polymers (EAP), and magnetostrictive actuators—allowed integration of sensing, actuation, and control within a single system for real-time, precise motion. Driven by applications in aerospace, medical robotics, manufacturing, and MEMS, research has focused on actuator principles, material properties, control strategies, and system integration. Key challenges identified include nonlinearity, hysteresis, thermal effects, and energy efficiency. Control methods like PID, adaptive, and model-based approaches have been explored to improve performance. This work outlines a systematic design methodology involving material selection, modeling, sensor integration, and feedback control. Performance is evaluated based on accuracy, response time, force, and efficiency, with comparative analysis highlighting strengths and limitations of different actuator types. Results indicate that smart actuators significantly enhance robotic precision and stability when combined with advanced control systems. Future research directions include hybrid actuators, improved materials, and advanced control algorithms.

KEYWORDS

Smart Actuators, Precision Robotics, Piezoelectric Actuators, Shape Memory Alloys, Electroactive Polymers, Adaptive Control, MEMS, Robotics Automation.

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1. INTRODUCTION

1.1. Background

The accelerated development of the robotics has posed a great demand on the development of highly precise, fast, and reliable actuation systems that are able to support the requirements of current applications. Conventional actuators, including hydraulic and pneumatic are also efficient in power and robustness but in contrast to other actuators, they are not as accurate and controllable as finer movements and precision need. Smart actuator systems have come up as a viable solution to these shortcomings by combining actuation, sensing and control into a logical system. Before 2018, the work devoted to this area was mainly aimed at increasing the characteristics of materials, better control accuracy, and reducing the complexity of the systems. The smart actuators use new materials which are capable of reacting to external stimuli like electrical, thermal, or magnetic signals to provide exact control of displacement and force. Also, with the integration of embedded sensors, real time monitoring and feedback is enabled, which is critical to high precision robotic application accuracy and stability.

1.2. Importance in Precision Robotics

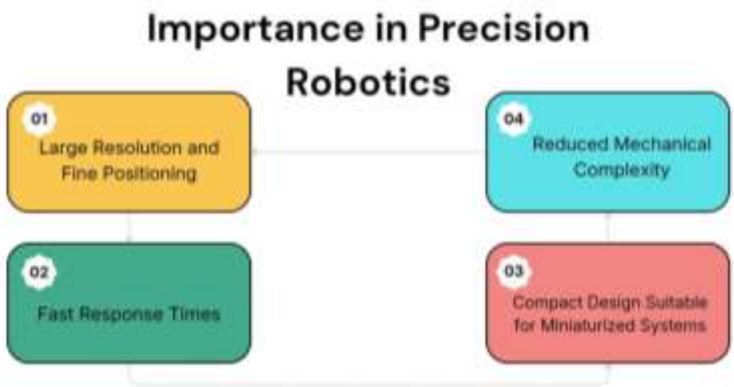

Fig 1 - Importance in Precision Robotics

1.2.1. Large Resolution and Fine Positioning

The very high resolution and fine positioning that is possible with smart actuators is required by highly precise robotic applications of actuators, including surgical work and micro-manipulation tasks. These actuators are able to generate extremely small and precise movements at both micro and even nano scales, with the highest precision and repeatability. This ability enables the robotic systems to execute delicate tasks with high precision, minimizing the chances of damage and enhancing overall functionality.

1.2.2. Fast Response Times

The other major benefit of smart actuators is that they have a rapid response, which means that they react promptly to control signals. This high-speed actuation is essential in dynamic situations, where quick adaptations are needed, including real-time operation in a surgical system or aerospace a control system. The shorter response time can make the system more efficient, minimize the delays, and increase overall responsiveness of robotic operations.

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PP: 01-12.

1.2.3. Compact Design Suitable for Miniaturized Systems

Smart actuators are usually small and light in weight, and thus are very suitable in miniaturizing robotic systems. Their small size allows them to be used in applications where space is limited, such as medical devices, micro-robots, and embedded systems. This small size makes it easy to integrate, as well as it helps to make advanced robotic solutions portable and flexible.

1.2.4. Reduced Mechanical Complexity

Smart actuators are much simpler to maintain mechanical complexity because they combine sensing, actuation and control into a single system. This integration reduces the complexity of the system architecture by minimizing the number of other components (gears, linkages and external sensors, etc.) required. The net effect is that the overall reliability is enhanced, the maintenance needs are reduced and the system is more efficient and the system is more efficient and easier to design and implement in precision robotics.

1.3. Challenges in Smart Actuator Systems

Although smart actuator systems have many benefits in the field of precision robotics, there are a number of limitations to their implementation that may impact their performance and reliability. Nonlinearity and hysteresis is one of the main problems and is prevalent with materials like piezoelectric and magnetostrictive actuators. These effects create a delay between the input and output resulting in inaccuracies and complicating the controlled process. This leads to the need to reduce these nonlinear behaviors with advanced compensation methods and advanced control algorithms. Thermal sensitivity is another major obstacle especially in actuators such as shape memory alloys, which is very sensitive to changes in temperature. Temperature variations may also cause a modification in the material properties, which can lead to an increase or decrease in response time, efficiency, and repeatability, which could be an issue in an environment with changing thermal conditions. Also, the range of displacement of many smart actuators is limited, particularly piezoelectric actuators which are very precise, but only in the case of very small motions. This is a disadvantage as it limits their use in activities where large-scale motion needs to be provided unless other mechanically-enhancing strategies are employed. Moreover, some actuator materials are energy-inefficient, especially those that are based on thermal or magnetic processes, in which some of the input energy is wasted as heat or by internal damping. Not only does this decrease overall efficiency, it can also cause overheating and a shorter life of a system. All these issues point to the necessity of further studies in material science, actuator design, and control strategy to increase the performance, efficiency, and applicability of smart actuator systems to higher robot tasks.

2. *LITERATURE SURVEY*

2.1. Early Developments in Smart Actuators

Prior to 2018, fundamental work in smart actuator technologies had a profound influence on the domain of precision robotics through investigations of advanced smart materials with the potential to convert energy into precise motion control. Piezoelectric actuators became a leading solution to nano-positioning operations because they are highly accurate, quick in response time and

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PP: 01-12.

can be used in micro- and nano-scale resolutions, thus being very useful in nano and microscopy, fabrication of semiconductors and precision alignment systems. Simultaneously, Shape Memory Alloys (SMAs) were also investigated due to their unusual properties of large deformation and recovery of their initial shape with the influence of thermal stimuli, allowing them to be used in small and flexible robots; but their slow response rate and thermal sensitivity were limiting in high-speed applications. Magnetostrictive actuators were also important contributors, especially in vibration control services, and high-force services because they have high response rate and a high force density in case they are subjected to magnetic fields. In these classes of actuators, scholars have mainly concentrated on solving the major issues of nonlinear behaviour, hysteresis, and lack of repeatability, creating compensation strategies and novel material structures to overcome actuator linearity, consistency and performance in precision-based applications.

2.2. Control Strategies in Smart Actuation

The success and stability of smart actuator systems is largely reliant on the efficiency of control methods used to address the nonlinear/dynamic nature of smart actuators. Proportional-Integral-Derivative (PID) control is one of the simplest and most commonly used methods, which is simple, easy to implement, and acceptable performance across a wide range of industrial applications; nonetheless, its performance is frequently poor when very nonlinear behaviors and time-varying system parameters are encountered. In order to address these difficulties, adaptive control methods were proposed, which allowed systems to adapt their control parameters dynamically, depending on the changes of the system dynamics and environmental conditions, thus enhancing the robustness and precision of the systems in uncertain situations. Moreover, the application of the Model Predictive Control (MPC) became popular because of its capability to predict the future behavior of the system based on mathematical models and optimize control actions under the conditions of system limitations including actuator limits and safety needs. MPC is especially useful in highly-complicated robotic systems that have multiple variables and constraints to control. All these control strategies are an advancement in the simplistic linear control towards more intelligent and predictive control approaches, and reflect the trend towards achieving greater accuracy, flexibility and efficiency in smart actuation systems.

2.3. Comparative Analysis of Actuator Types

An overview of the various types of smart actuators shows a trade off among the performance parameters of precision, force output, response speed and structural complexity, which directly affects their applicability to a particular application. Piezoelectric actuators have a relatively small displacement range but are highly known to be precise and quick making them ideal in applications where fine positioning is required; though, they are limited in the range of displacement that they have. By contrast, Shape Memory Alloys (SMAs) have important strain and compact design benefits, allowing huge deformations in small volumes, but have slower responsiveness and energy efficiency that restricts their use in high-freqency applications. Electroactive Polymers (EAPs) offer a novel, lightweight and flexible alternative, commonly employed in the field of soft robotics because of their capacity to replicate biological motions, but with limited force generation and durability issues.

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PP: 01-12.

Magnetostrictive actuators are high-force and quick-response devices, which can be used in vibration control and heavy-duty applications but demand more complicated control systems and tend to be more costly. This analogy emphasizes the need to choose the actuator technologies according to the specifics of the applications, considering the benefits and drawbacks to attain the highest performance of precision robotic systems.

3. METHODOLOGY

3.1. System Architecture

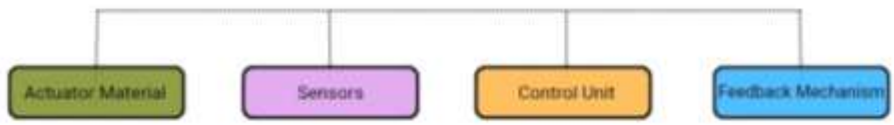

Fig 2 - System Architecture

3.1.1. Actuator Material

The core part of the smart actuator system is the actuator material, which transforms input energy (electrical, thermal or magnetic) into mechanical motion. Piezoelectric ceramics, shape memory alloys (SMAs), electroactive polymers (EAPs), and magnetostrictive materials are common materials with their own distinctive properties, including high precision, large deformation, and high force output. Actuator material is chosen based on the individual needs of the application, such as the response speed, displacement range, and environmental needs because the choice directly affects the performance, efficiency and reliability of the system.

3.1.2. Sensors

Sensors are an important component to measure the real time status of the actuator system in terms of displacement, force, temperature and vibration. Such sensors offer precise and continuous data, which are representative of the actuator performance and the state of operation. Smart actuator systems are commonly fitted with advanced sensing devices such as strain gauges, optical sensors and capacitive sensors in order to guarantee high-resolution sensors, which are critical in the pursuit of fine control and stability in the system.

3.1.3. Control Unit

The control unit is the brain of the smart actuator system, which interprets the input commands and sensor data to produce the right control signals to take to the actuator. It is often composed of microcontrollers, digital signal processors (DSPs), or embedded systems that execute control algorithms like PID, adaptive control or model predictive control (MPC). The control unit also maintains the actuator to desired performance criteria by reducing errors, nonlinearities, and adaptation to changing system dynamics in real-time.

3.1.4. Feedback Mechanism

A feedback mechanism is a key element that allows closed-loop operation in smart actuator systems, as it allows a continuous comparison between the actual and desired output. Through the

ISSN: 3071-5725
PP: 01-12.

comparison, corrective measures are done to minimize errors and enhance accuracy. The system can respond dynamically to feedback by means of different sensors and feeding the feedback into the control unit. The mechanism leads to greater accuracy, stability, and durability, especially in systems where high precision and repeatability is needed, like precision robotics and micro-positioning systems.

3.2. Mathematical Modeling

Smart actuator systems have behaviour which can be well represented by mathematical models that describe their mechanical and electromechanical behaviour. A popular model of representation assumes that the actuator is a mass-spring-damper system with the force generated being a displacement-velocity-dependent function. This correlation is given as:

The force generated by the actuator in this model is the product of stiffness coefficient, and displacement plus the damping coefficient and velocity. In this case, the stiffness is the actuator material resistance to deformation and the damping coefficient is the energy dissipation due to internal friction and material properties. This equation can be used to formulate the dynamics of actuator response to external inputs, and it is of great use in designing control systems where stability and accuracy are crucial. The term displacement, is how far the actuator has gone out of its equilibrium position, and the term velocity is how rapidly the actuator moves. Collectively, they characterise the transient and steady-state behaviour of the actuator, and the model is fundamental in forecasting performance in the different operating conditions. In the case of piezoelectric actuators, the connection between the electrical input and the mechanical output is more precisely represented by a linear electromechanical equation. This equation implies that the magnitude of the displacement caused by the actuator is proportional to the voltage applied to it with the proportionality constant being the piezoelectric coefficient. The coefficient is the capability of the material to transform electrical energy into mechanical strain. Higher is an indication of higher displacement at a voltage. This linear model is especially handy in precision applications, though in practice nonlinearities like hysteresis and creep could have an impact. In general, these mathematical models offer a framework of understanding actuator behavior and allow engineers to develop effective control strategies and optimization of system behavior in precision robotic applications.

3.3. Control Algorithm Design

3.3.1. System Identification

The first step in the design of control algorithms is system identification, in which experimental data or theoretical modeling are used to analyze and characterize the dynamic behavior of the actuator system. The main parameters to be determined in this process are stiffness, damping, response time, and nonlinear effects like hysteresis. To develop effective control strategies, the identification of the system should be done accurately as it gives a solid representation of the behavior of the actuator which is the basis of the control strategy development. Frequency response analysis, step response testing, and parameter estimation methods are some of the techniques that are commonly utilized in order to obtain accurate system models.

ISSN: 3071-5725
PP: 01-12.

3.3.2. Model Formulation

The process of model formulation consists of the translation of the characteristics of the identified system into mathematical equations reflecting the behavior of an actuator under various operating conditions. Such models may be linear or nonlinear depending on the complexity of the actuator dynamics and are applied to model the performance of the system. A good model reflects key features of input-output relations, system constraints and perturbations. This is an essential step in the prediction of the actuators behavior to control inputs and in the design of controllers with the capability to attain the desired performance goals like accuracy, stability, and speed.

3.3.3. Controller Design

The controller design is concerned with the design of algorithms to control the actuator behavior to produce the desired outputs. According to the developed model, appropriate control measures, including PID control, adaptive control, or model predictive control (MPC) are chosen and adjusted. The controller aims at reducing the discrepancy between the desired and actual output, and stability and robustness of the system. This step can include simulation and optimization methods to optimize controller parameters to ensure that the actuator works effectively in different conditions and perturbations.

3.3.4. Real-Time Feedback Implementation

The last step is real-time feedback implementation, which involves the integration of the designed control algorithm with sensors and hardware to run the actuator in a closed-loop system. The sensor data is fed back to the controller which is continuously monitored and used in the dynamically adjusting control signals as system behaviour changes. This guarantees high accuracy, rapid error detection, and enhanced reliability of the system. The high-speed processors and efficient communication protocols are frequently needed to implement real-time to achieve low latency and guarantee that the actuator is correct in time-sensitive systems like robotics and automation systems.

3.4. Flowchart of Smart Actuator Operation

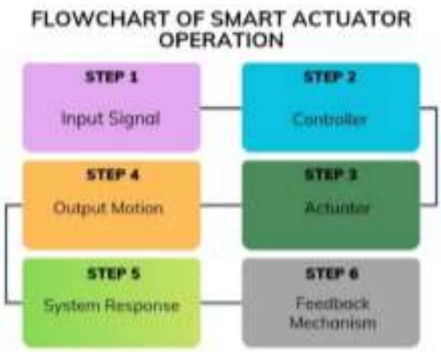

Fig 3 - Flowchart of Smart Actuator Operation

3.4.1. Input Signal

A smart actuator system works with the input signal, which is the desired command or reference of the system. This signal can be a user interface, a higher level control system or a

ISSN: 3071-5725
PP: 01-12.

programmed command in a robotic application. The input is what determines the necessary position, force, or movement that the actuator should attain. It acts as the point of reference in the control process and it gives the guide or benchmark against which the performance of the system is measured.

3.4.2. Controller

The input signal is fed into the controller, which uses control algorithms like PID, adaptive, or model predictive control to process the input signal. It compares the desired input to the feedback sent back by the system and decides the correct control action to be taken to reduce the error. The controller then produces a control signal which is transmitted to the actuator. This phase is very important in terms of accuracy, stability and effective system operation since the response of the actuator to the desired command is controlled.

3.4.3. Actuator

The actuator translates the electrical or control signal sent by the controller into a mechanical motion. This conversion can be done as electrical, thermal or magnetic energy conversion depending on the kind of actuator employed (e.g. piezoelectric, SMA or magnetostrictive). The actuator itself performs the actual physical motion necessary (e.g. displacement or rotation or force production) and thus directly affects the output of the system. The nature of its performance is a major determinant of system total accuracy and responsiveness.

3.4.5. Output Motion

Output motion this is the actual physical response of the actuator, which can be linear displacement, angular rotation or applied force. The output is the actualization of the input command and is used to carry out a desired task in applications such as robotics, automation or precision positioning. Both the performance of the actuator and the quality of the control system influence the quality of the output motion, its accuracy and smoothness.

3.4.6. Sensors

The system response is constantly monitored by sensors that measure the important parameters (position, velocity, force, or temperature). These measurements give real time information on the performance of the actuator against the desired performance. Precise sensors are needed to obtain precise information, which is required to realize proper feedback management. They are the mechanism of observation in the system and they make sure that whenever there is deviation in the desired behavior, then it is detected fast.

3.4.7. System Response

The system response is the behavior of the mechanical system and the actuator following the application of the control signal. It incorporates all dynamic effects like delays, oscillations and nonlinearities that can arise during operation. The system response is influenced by factors like load conditions, environmental disturbances, and material properties. This response is significant in understanding the performance of the system and enhancement of control strategies.

ISSN: 3071-5725
PP: 01-12.

3.4.8. Feedback Mechanism

The sensor measurements are fed back to the controller by the feedback mechanism that completes the control loop. This enables the controller to compare the real output against the desired input and real-time adjustments are made. Feedback is important to ensure the stability of a system, minimize errors, and improve accuracy. The feedback loop enables the smart actuator system to work efficiently and reliably in dynamic and uncertain conditions by constantly correcting the deviations.

4. RESULTS AND DISCUSSION

4.1. Performance Evaluation Metrics

The performance of the smart actuator systems is measured in terms of a number of key parameters such as accuracy, response time, energy efficiency as well as force output, all of which are important in evaluating the effectiveness and applicability of the actuator to precision robots. Accuracy is the degree to which the actuator can reach the desired position or output with a small error, and is particularly significant in such application areas as micro-positioning and surgical robotics where even minor errors can result in serious performance problems. Response time is the rate at which the actuator responds to an input signal, which is the rate at which the system is operating; the response time should be quick in dynamic systems where rapid changes are needed. The other parameter of interest is energy efficiency, which is an indicator of the means by which the actuator changes input energy to useful mechanical work with minimal loss through heat, friction or material inefficiencies; besides lowering the cost of operation, high energy efficiency also increases system performance and lifespan. The force output is a property of the actuator that defines its ability to produce enough mechanical force to execute a desired task, especially when it is necessary to handle a load or overcome resistance. These measures are usually mutually reliant and thus should be carefully optimized to balance precision, speed, power consumption and mechanical strength. The measurement of these parameters gives a holistic figure of the actuator performance and assists engineers in designing systems that can perform to certain requirements in terms of high reliability and efficiency.

4.2. Comparative Performance

Table 1: Comparative Performance

Actuator Type	Accuracy (%)	Response Speed (%)	Efficiency (%)	Force Output (%)
Piezoelectric	95%	90%	80%	70%
SMA	85%	60%	75%	85%
EAP	80%	85%	70%	60%
Magnetostrictive	88%	75%	78%	90%

4.2.1. Piezoelectric Actuators

The accuracy of piezoelectric actuators has reached 95 percent and therefore they are well suited to precision critical systems including nano-positioning and micro-manipulation systems. They also have a very high response speed of approximately 90% because response occurs quickly through the electromechanical conversion process and therefore respond nearly instantly to the input signal. They are efficient (around 80) in converting electrical energy into mechanical motion, but some internal damping and hysteresis result in energy losses. They, however, have a relatively moderate force output of about 70 which restricts their application to heavy-load applications yet they are very appropriate in fine applications.

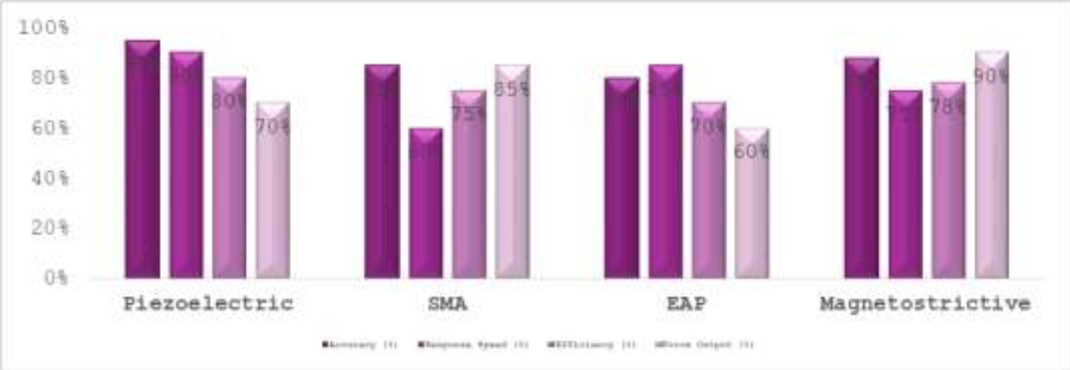

Fig 4 - Comparative Performance

4.2.2. Actuators: Shape Memory Alloy (SMA)

Shape Memory Alloy actuators provide a compromised performance that is accurate to approximately 85% that is adequate in most engineering applications. Their most pronounced strength is their high force production, which is around 85% and allows them to produce high mechanical force, in small designs. Nevertheless, they are relatively slow in response, about 60% because of the thermal activation mechanism necessary to change phases, slowing the actuation cycles. SMA actuators have a relatively low efficiency (around 75) but the efficiency is affected by the energy losses involved in heating and cooling cycles.

4.2.3. Electroactive Polymer (EAP) Actuators

Electroactive Polymer actuators are average accuracy at 80% and are especially treasured because of their flexibility and light weight. Their reaction time is fairly quick, at around 85 percent, enabling a ease and rapid actuation, helpful in soft robotics and biomimetic. They are however a little less efficient with a rate of approximately 70 and also with the lowest force output of about 60 when compared to the other actuators, they are not applicable to applications where a lot of القوة or load bearing is needed. Regardless of these constraints, their weight and flexibility make them suitable to innovative and flexible systems.

4.2.4. Magnetostrictive Actuators

Magnetostrictive actuators provide a good combination of performance parameters and an accuracy of about 88 percent and a response time of approximately 75 percent, which makes them dependable in the precision and dynamic use. They are relatively efficient with a conversion rate of about 78 per cent. since they can efficiently transform magnetic energy into mechanical motion. Their high force production (up to 90 percent) is one of their most important assets, and they can be used in heavy-duty operations like vibration control as well as in industrial equipment. Nonetheless, this complexity in control and their increased cost may be viewed as a limitation in some applications.

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PP: 01-12.

4.3. Discussion

The comparative study of smart actuator technologies reveal that both types of actuators have their own advantages and disadvantages and can be applied to various types of applications in precision robotics. Piezoelectric actuators are most effective, not only because of their high accuracy and fast response time but also because of their ability to be actuated virtually instantly with a very low positional error. This renders them very attractive in uses like nano-positioning, optical systems, and semiconductor manufacturing, where accuracy is paramount. The fact that they have a relatively small displacement range, however, limits their use in applications that need large movement or long stroke length, and thus it is necessary to use amplification mechanisms or hybrid systems to overcome this limitation. Conversely, Shape Memory Alloy (SMA) actuators have been identified to produce high force and massive deformation in small-scale structures and hence they are beneficial in the space-constrained structure and load-bearing structure. Although this has advantages, they have slow response times caused by thermal activation and cooling times and thus they do not respond well in high-speed or real-time systems. The magnetostrictive actuators have a balanced performance with a relatively high force output, moderate response speed and good accuracy and are therefore applicable in vibration control and precision actuation situation under dynamic conditions. Nevertheless, their need to have complicated control mechanisms and sensitivity to magnetic field changes add complexity and cost to the system. In general, it has been pointed out that the actuator should be chosen in accordance with the application, and it is necessary to take into account trade-offs between precision, speed, displacement, and complexity of control to obtain optimal system performance.

5. CONCLUSION

Smart actuator systems have been shown to be a revolutionary step in the development of precision robotics, especially during the era before 2018 when a lot of background research was done to define their principles of operation, capabilities, and inherent constraints. Intelligent materials like piezoelectric components, shape memory alloys, electroactive polymers, magnetostrictive components, and others have been integrated into these systems, leading to design of highly responsive and precise robotic mechanisms. Inclusion of improved sensing technology and feedback systems have also improved system reliability by enabling real time monitoring and correction of actuator behavior. Moreover, the development of control techniques and methods, such as traditional PID controllers, adaptive, and model predictive control methods have greatly enhanced the accuracy, stability, and efficiency of smart actuator systems in dynamic and challenging conditions. Consequently, such systems have been widely used in areas of medical robotics, aerospace engineering, micro-manufacturing, and automation, where great accuracy and responsiveness is needed. It is evident that not one type of actuator is universally optimal as the study shows each technology has a mix of advantages and disadvantages. An example is piezoelectric actuators, which are most effective with high-precision and high-response applications, but have small displacement limits, whereas shape memory alloys have large deformation and high force output at the expense of slower response times because of thermal dependencies. Likewise, magnetostrictive actuators will offer a more balanced performance but with more complex control systems, and electroactive

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PP: 01-12.

polymers will provide lightweight and flexibility with relatively low force production. These variations make it clear that the choice of actuators depends on the specific application needs and should consider aspects like accuracy, speed, force, energy consumption and complexity of the system. In the future, it can be predicted that further advancements in smart actuator systems will be aimed at addressing the current limitations by designing hybrid actuator systems that can be used to integrate the benefits of various materials and technologies. Increases in material science such as new smart materials with improved properties will enable even better performance of actuators. Also, the combination of artificial intelligence and machine learning-based control methods are highly promising in facilitating more adaptive, self-optimizing and intelligent actuation systems. These developments will open the door to the next generation of precision robotic systems with the ability to attain new and higher levels of efficiency, versatility, and autonomy in more challenging tasks.

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