



# Actuators with Force Feedback: A Literature Review in the Scope of Educational, Academic, and Industrial Applications

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**Abstract.** Force sensors are essential elements of actuator systems, providing measurement and force control in different domains. This literature review discusses its applications in the industry, academic research, and educational domains. In an industrial setup, force sensors enhance efficiency, safety, and reliability within automation systems, predominantly robotic arms and assembly lines. In the academic environment, using such sensors fosters innovation within robotics and biomechanical studies, allowing for testing theoretical models and new methodologies. In education, force sensors help students understand basic concepts about mechanics and robotics from practical work. Understanding this diverse application allows one to design effective actuator systems, promoting technological advances and improved learning experiences. With this literary review, the aim is to gain an understanding of the state of the art in force sensor actuators applied in various areas, such as academia, education, and industry.

**Keywords:** Force sensor · Industry · Academic · Educational · Review

## 1 Introduction

Force sensors have become a critical technology in developing actuator systems, enabling them to offer precise measurement and control capabilities cutting

across different domains [1,2]. Their applications range from industrial automation and academic research to educational environments; the system requirements and implementations differ in all these cases. This paper investigates the multidimensional use of force sensors within actuators and new trends in how their integration differs between industry, academia, and education.

In industries, force sensors are applied to enhance efficiency, safety, and reliability in automated systems [3–6]. They allow precise control of robotic arms, assembly lines, and automated manufacturing. The sensors perform at a constant quality without any breakdown in operation. Industrial applications will thus call for a force sensor that is robust enough to ensure high precision under hostile environmental conditions and is continuously used.

On the other side, academic research focuses on innovation in developing and optimizing actuator systems. In this sense, detailed information is acquired through force sensors, which drive the development of robotics, biomechanics, and materials science. Turned around, researchers apply these sensors to experiment, verify theoretical models, and define limitations in new technological frontiers. The main concerns in academia are researching new methodologies to improve the performance of actuator systems with test and analysis [7,8].

In educational backgrounds, force sensors are useful as instructional devices that facilitate learners to comprehend fundamentals of mechanics, robotics, and control systems [9–11]. It is possible to involve students in practical experiments relevant to how theoretical knowledge can be applied using these sensors with the assistance of laboratory exercises and projects. The most typical set of sensors used in educational institutions is user-friendly, low-cost, and multi-use so that they can serve different instructional setups conveniently [12].

## 2 Applications of Force Sensors in Different Environments

Force sensor applications span various industrial, academic, and educational settings. Understanding and developing robotic systems tailored to these various settings is crucial based on their goals, requirements, environment, and constraints.

### 2.1 Industrial Applications

*Goals and Focus:* Efficiency and productivity are the main goals for applications with force sensors in the industry. These systems are applied to enhance operational efficiency, increase production rate, and lower overall process cost [13–15]. Accuracy and reliability have to be very high to meet strict quality standards. These actuators are designed to perform consistently without making any errors to attain good product quality and minimum wastage. In [16], a novel framework is introduced to evaluate the performance of pick and place operations by industrial robots, where data was acquired using a 6-axis force/torque sensor. Automating repetitive, hazardous, or labor-intensive tasks is emphasized to improve workplace safety and allocate human workers to more complex activities [17–19].

*Environment:* The industrial environment is typically highly controlled to improve robot performance. Variables like temperature, humidity, and lightning are managed to achieve maximum robot performance. The operations are usually large-scale, which involve a vast assembly or packaging facility in which the robots do high-volume work in large industrial settings [20].

*Technology and Features:* Industrial systems are built robustly and can operate under severe temperatures, dust, humidity, and high-duty conditions. This durability is essential to minimize downtime and maintenance. In this setting, the actuators are built in highly specialized ways for specific given tasks like welding, painting, assembly, or material handling, with their features customized to each function [21–23]. Integrating other automatic systems, such as conveyor belts, CNC machines, and quality control systems, should be practical and seamless. In [24], it proposed a novel shape-matching method for robotic grinding using a laser scanner.

## 2.2 Academic Applications

*Goals and Focus:* The focus in academia is research and innovation. For robotic systems, new algorithms, techniques, and theories focus on developing state-of-the-art robotics and developing new solutions [25–30]. An example is [31], which models 3D models through haptic exploration in blind scenes using forces/torque sensors. Or in [32] that reports a MEMS sensor for measuring the force acting on the spike pins of athletic sports shoes. Flexibility is a critical condition that lays out the development of systems that can be adapted to multiple tasks and environments [33–37]. At the core of all academic applications lies the experiment, and it is through controlled testing that robots will be used to validate theoretical models and hypotheses [38].

*Environment:* Academic research occurs within a laboratory environment, which is often re-configurable to change test conditions [39]. These environments are highly dynamic; they keep changing, testing new ideas and configurations. This makes the lab versatile because researchers can experiment with scenarios and conditions supporting a broad range of research [40, 41].

*Technology and Features:* Most academic setups use experimental and prototype hardware and software, integrating the latest technologies that are still in the development stage [42, 43]. Especially for versatility and capability, the robots are equipped with different sensors and actuators to cover diverse research goals. Below is an implemented control for grasping objects through a robotic manipulator designed by [44] through the design and implementation of three controllers: a classic PID controller, a type-I controller, and a type-II fuzzy controller. The systems are modular in design and, hence, easy to reconfigure for upgrading and according to the changes that will necessarily arise due to the iterative nature of academic research.

### 2.3 Educational Applications

*Goals and Focus:* The educator intends to give students the principles of robotics, programming, and engineering. A robotic system should be a tool that engages and inspires students to learn essential concepts to build interest in STEM (Science, Technology, Engineering, and Mathematics) [45–47]. It has to be accessible, safe, and user-friendly for students of all age groups and at different skill levels.

*Environment:* Educational robots are used in an environment that is a classroom, lab, or workshop, all areas being learning and experimental settings [48]. These settings are important as they ensure safety and interactivity to facilitate hands-on learning and a positive and engaging educational environment. In [49] presents a three-dimensional (3D) virtual laboratory simulation system for physics education.

*Technology and Features:* The design of educational systems is usually straightforward, making them easy to assemble, program, and execute [50]. They are also cheap and easily obtainable by educational centers. Secondly, the designs of educational robots incorporate supporting systems and software for visual programming languages with interactive tutorials to add flair to learning in that process, thus making it easy to program in robotics [51, 52].

Knowledge of these characteristic differences in application and consequent requirements guides stakeholders in designing and implementing force sensor systems better for particular industrial, academic, and educational needs, leading to technological advancements driving innovation and learning in cross-disciplinary fields.

## 3 Research Questions

A series of questions are posed to analyze the state-of-the-art force sensor deeply, applied in actuators in various areas.

### 3.1 What Are the Prevalent Applications of Force Sensors in Manipulators Across Different Industries?

Force sensors play a crucial role in manipulators across various industries by providing precise feedback and control for different tasks. One of the most common applications for the force sensor is related to a process where the end-effector needs constant pressure against the working piece. In [4, 22], a control system and actuators are designed for polishing; in [13], apply force/torque sensor for industrial deburring process; in [3, 5, 21], the process is grinding, and in [15, 24] for cleaning and tooling respectively.

In assembly lines, force sensors ensure that parts are assembled with the correct force, reducing the risk of damage and improving the fit and finish of the final product. In [14, 16], with the use of information obtained by a 6-axis

force/torque sensor, the architecture makes it possible to detect in real-time when an object is slipping during the picking. In [20], develop a force-sensing glove worn by workers in manual assembly to measure both shear and normal forces and motion data to evaluate the connections completed and provide real-time feedback to the operator.

### **3.2 How Do Industrial Organizations Integrate Force Sensing Technology Into Their Robotic Systems for Enhanced Performance and Safety?**

Integrating force sensing technology into robotic systems involves several strategic steps to enhance performance and safety in industrial applications. [17, 18] propose collision detection approaches using a force/torque sensor at the end-effector in order to increase safety, and in [19], a novel 7-DOF (degree-of-freedom) upper-limb robotic exoskeleton was developed for helping refractory construction operations in furnaces.

### **3.3 What Are the Latest Advancements in Force-Sensing Technology in Manipulators from Academic Research?**

Researchers focus on creating high-resolution tactile sensors that provide detailed force and pressure distribution feedback. In [33, 36], the systems are presented, enhancing the precision in the sensor reading by compensating for the effect of the gravity in the actuator.

Advances in materials science have led to the creation of soft and flexible force sensors that can conform to complex shapes. These sensors are particularly useful in applications where the manipulator needs to interact with soft or irregularly shaped objects, such as in medical robotics or agriculture. [26] introduce a contact force sensor based on three 'dyadic-S-shaped' beams and three optoelectronic sensors for flexible manipulators for minimally invasive surgery. [23] presents a micro-3-degree of freedom (DOF) force sensor with a length of only 3.8 mm that can adjust the puncture angle during retinal vein cannulation (RVC). In [39], the development and test of a non-destructive robotic sensor for assessing dragon fruit quality related to texture deterioration is shown.

Utilizing AI and machine learning to process and interpret force sensor data in real time. Enhances the ability of manipulators to adapt to changing conditions and perform tasks autonomously, with improved accuracy and efficiency. In [34], a method for estimating end-effector forces using measurements from the base-mounted force sensor and deep neural networks is presented. [5] uses backpropagation networks to restore damaged force/torque sensors.

### **3.4 How Do Academic Studies Approach the Design, Implementation, and Validation of Force Sensors in Manipulators?**

Academic studies typically approach the design, implementation, and validation of force sensors in manipulators through a systematic process that includes the-

oretical development, experimental testing, and iterative refinement. Advanced manufacturing techniques such as MEMS (Micro-Electro-Mechanical Systems) for miniaturized sensors and 3D printing for rapid prototyping are being implemented. In [32] reports a microelectromechanical system (MEMS) sensor for evaluating the force acting on the spike pins of athletic sports shoes. [42] presents the characterization of a low-cost 3D-printed strain sensor fabricated using material extrusion (MeX) technology by using a conductive material composed of a polylactic acid (PLA) based matrix. In [38] discusses techniques for rapidly developing simple force sensors, including selecting and attaching metal flexures, using inexpensive and simple displacement transducers, and 3-D printing features to aid in assembly.

### 3.5 How Effective Are Educational Approaches in Bridging the Gap Between Theoretical Concepts and Practical Applications of Force-Sensing Technology?

Educational approaches are crucial in bridging the gap between theoretical concepts and practical applications of force-sensing technology. Practical exercises and experiments allow students to interact with force-sensing technology directly. The hands-on approach helps understand theoretical concepts such as force measurement, sensor calibration, and data interpretation in a real-world context. [9] propose HandsOn-SEA, a low-cost, single-degree-of-freedom, force-controlled educational robot with series elastic actuation, and introduce educational modules for the use of the device to allow students to experience the fundamental performance trade-offs inherent in robotic systems. In [10] is presented an educational experiment with a mechatronic system that demonstrates concepts such as prototyping, control, haptic feedback, and different sensors and actuators. [11] proposes, as an educational activity, the design of a system that allows the control of a robotic manipulator by using a sensory glove and an arm sleeve.

Virtual simulations and lab exercises provide a safe environment for students to experiment with force sensors without the need for expensive equipment. These tools can simulate various scenarios and allow students to visualize abstract concepts. [49] proposes a 3D virtual laboratory simulation system for physics education. The system uses available motion sensors by considering the advantages of both 2D and 3D virtual environments. [46] presents a program for robotics education that runs on standard PCs under the Microsoft Windows environment. The RobLib package is designed for undergraduate students and emphasizes the fundamental aspects of robot modeling and control.

## 4 Conclusion

Actuators with integrated force sensors are regarded to have multi-faceted applications in the industrial, academic, and educational domains. These sensors enhance operational efficiency, productivity, and safety in industrial settings, proving their indispensability in robotic assembly lines, welding, painting, and

material handling applications. The robustness and precision required in these environments ensure consistent performance under harsh conditions, contributing significantly to quality control and reducing operational costs.

In academic research, force sensors play important roles in innovation and experiments. Force sensors help to create and prove new theories, algorithms, and technologies in these areas, especially in robotics, biomechanics, and materials science. The flexibility and adaptability of a laboratory setup make it possible for scientists to carry out experiments with every scenario and condition to foster further advancements that can be transferred to practical applications.

In educational environments, force sensors are employed to bridge the gap between theoretical knowledge and its practical application. Cost-effective and easy-to-use sensors work flexibly in operation so that students can understand basic concepts of mechanics, robotics, and control systems. The force sensor will draw an impression and ignite interest in becoming the next engineer or scientist by involving the student in an interactive practical exercise. Integrating force sensors into actuators greatly impacts precision, control, and reliability improvements. Research and development in the near future should be directed toward advancing sensor technologies, their integration with other systems, and their use across new application fields. Additionally, industry, academia, and education stakeholder needs and applications help better design and implement force sensor systems that enhance innovation and learning across multi-disciplinary areas.

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