EXPERIMENTAL SYSTEM FOR MEASURING THE BENDING STIFFNESS OF SOFT ACTUATORS BASED ON SERVO DRIVES

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This article deals with the design, construction, and testing of a new system for measuring the stiffness of soft actuators. These actuators move similarly to living organisms using flexible materials and internal pressure. The study presents a comprehensive method that combines sensors, actuators, and control systems to measure the force developed when the actuator is bent or stretched. Much of the work involves creating an experimental setup that uses a linear axis, force sensors, and programmable controllers to collect accurate data. By studying the behaviour of the actuator under different pressures and movements, the research helps improve the design and use of soft actuators in areas such as robotics, rehabilitation, and intelligent automation. The results highlight the need for accurate measurement tools to make actuators more reliable and useful. The system developed in this study could lead to standard testing methods for soft robotics in the future.

KEYWORDS

soft actuators, stiffness measurement, strain gauge sensor, control systems, robotics, adaptive automation

1 INTRODUCTION

The evolution of engineering and robotics has been marked by a growing interest in materials and structures that can mimic biological systems, leading to the development of soft actuators. These innovative devices, which feature the use of flexible materials, have shown remarkable promise in applications ranging from healthcare to robotics, primarily due to their ability to perform complex movements in a gentle manner that is often safe for human interaction [Massari 2022].

The importance of soft actuators lies in their ability to bridge the gap between rigid mechanical movements and organic, adaptive interactions that occur in nature, enabling advances in fields such as rehabilitation, prosthetics, and precision engineering [Nafiseh 2020].

Current literature highlights several key themes related to the development and application of soft actuators, including advances in materials science, the integration of sensing technologies, and the improvement of control systems, as evidenced by numerous studies [Forcael 2020].

The emergence of soft actuators represents a significant advance in robotics and artificial intelligence, offering a flexible alternative to traditional rigid mechanisms. These actuators are made of flexible materials and enable more adaptive and biologically inspired motion, making them ideal for use in healthcare, manufacturing, and environmental monitoring [Massari 2022]. With the expansion of these applications, the demand for reliable soft actuators is growing, but their wider practical use continues to be limited by challenges such as durability, response time, and control accuracy [Nafiseh 2020, Forcael 2020].

The aim of this research is to systematically analyse the current state of soft actuators, highlight challenges in performance and integration, and categorize their diverse applications [Chunguang 2020]. The goal is to bridge the gap between theoretical advances and real-world implementation and ultimately provide information on how these technologies can evolve to meet new industry needs [Shafique 2020, Kumar 2021]. Key objectives include investigating actuator design and material behaviour under different pressure conditions, evaluating application-specific results, and gathering feedback from users to guide future innovation [Doolani 2020]. By supporting innovation in materials science and design, this work aims to improve the reliability and functionality of soft actuators [Xiloyannis 2019].

One of the highlights importance of interdisciplinary collaboration to leverage soft actuator technology for transformative applications in various fields such as medicine, rehabilitation, and robotics [Gianluca 2018, Baoping 2017, Florea 2023]. The findings may influence future actuator design and establish these systems as an integral part of advances in human-robot interaction and automation [Cuomo 2022, Massardi 2023, Heng 2021]. Improved soft actuator technologies could significantly improve patient outcomes and industrial efficiency, reinforcing their broader significance in technological innovation [Sanfilippo 2025]. Although various use cases have been documented, further research is needed to fully understand their integration into complex systems such as collaborative robots (cobots) [Ometov 2021, Pech 2021].

Future research should focus on exploring new composite materials to achieve better performance, developing standardized testing protocols, and addressing ethical issues, particularly in the medical context, to promote responsible innovation. In conclusion, soft actuators represent a promising path towards safer, more adaptive, and more functional technical solutions. Progress in this field requires a holistic approach that considers technical, ethical, and sociocultural dimensions. Cross-sector collaboration will be essential to realize the full potential of soft actuators and transform key industries such as healthcare and robotics [Massardi 2023, Lin 2023].

2 METHODOLOGY

Sensor integration, selection and specification of actuators and data acquisition capabilities in control systems play a key role in the development and functionality of soft actuators. These systems are designed to provide adaptive and accurate responses suitable for complex environments, increasing the versatility of robotics in a variety of applications, including medical technology and human-robot interaction. As such, sensor integration is essential not only for improving the performance of actuators, but also for achieving the challenging goals of next-generation intelligent machines.

2.1 Types of sensors used to measure stiffness for soft actuators

The measurement of stiffness in soft actuators is essential to ensure their performance across a wide range of applications. Various sensors can be employed for this purpose. Strain gauges are commonly used due to their high sensitivity and their ability to provide real-time strain data under load. Similarly, piezoelectric sensors are effective in detecting dynamic changes in stiffness by converting mechanical strain into electrical signals, making them well-suited for fast-response applications. Another option is capacitive sensors. Which are advantageous since, they can measure the distance between actuator surfaces, thus allowing the calculation of stiffness based on displacement measurements. Each type of sensor offers different advantages, such as resolution and response, which are essential to the accuracy of the system. The integration of these sensor technologies, as discussed in, enables comprehensive monitoring and control of actuator behavior, ultimately improving the performance and reliability of soft actuators in practical applications.

3 CONSTRUCTION STRUCTURE OF THE MEASURING ASSEMBLY

This chapter details the design of the structural assembly as we want to measure the force required to deflect the soft actuator. This section describes and graphically illustrates the design solutions, and the tools used, which we have specified based on the necessary requirements for this purpose. For each device there is a description of the purpose for which this device will be used and his operating principles.

3.1 *SMC linear axis*

In industrial sectors, measuring the force required to deflect a body is important for the need to optimize performance and to ensure the safety and reliability of operations. Measuring the force required to deflect a body allows the properties of materials and the efficiency of mechanical structures to be evaluated, which is very important in industries such as manufacturing, aerospace and robotics. The introduction of modern measurement systems improves the ability to detect the force required to deflect the measured bodies in different mechanical configurations.

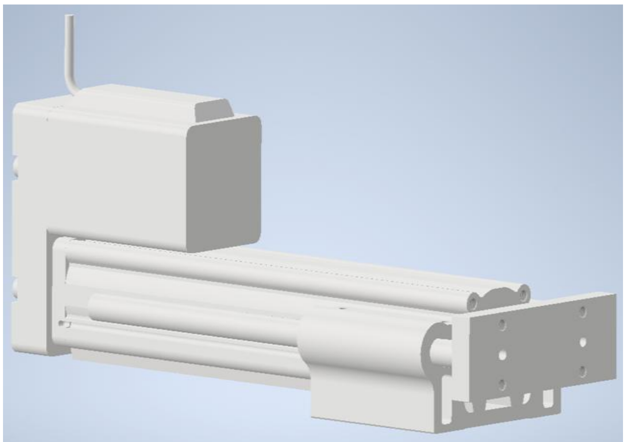

Figure 1. Linear servo axis used for stiffness measurement

The SMC LEYG40LEC-150C-R3C918 is an electric actuator from the LEYG series, designed with integrated guide rods to enhance lateral load resistance and eliminate torsional deflection, ensuring high positional accuracy (Fig. 1). It offers a 150 mm stroke and is driven by a 24 VDC stepper motor (servo type), delivering up to 1.058 N of thrust (Table 1). The actuator supports speed and multi-point positioning control with up to 64 positions, including push-motion operation, allowing the rod to maintain position under applied force. It achieves a positioning repeatability of ±0.02 mm, making it suitable for precision applications. The LEYG series supports both plain bearings and ball bushings, providing flexibility for different load and motion requirements.

Table 1. Table of technical specifications of SMC linear axis

Technical specifications	
Size	40
Bearing Type	Ball Bushing Bearing
Motor Mounting Position	Top Mounting
Lead	Size 32/40: 4 mm
Stroke	150 mm
Motor Option	w/Motor Cover
Guide Option	Without option
Actuator cable type, Length	R3, (3m)
Controller	C91 (Ether Net/IP™)
Mounting	8 (DIN Rail)
Communication Plug Connector, I/O Cable	None

3.2 *JXCP*

The JXCP controller serves as the primary communications component that reads input signals, executes predefined logic sequences, and issues appropriate output commands to actuators or other system components (Fig. 2). Its characteristics generally accommodate both analog and digital input/output settings, increasing its versatility in complex industrial environments.

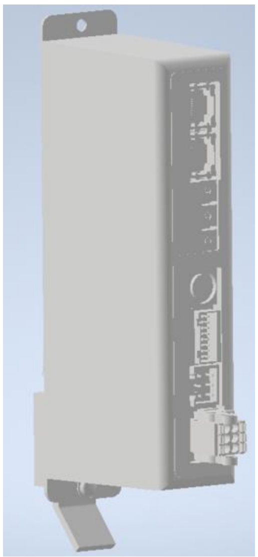

Figure 2. Servocontroller JXCP with communiacation Ethernet/IP

The JXCP unit features compatibility with standardised communication interfaces including Modbus, Ethernet/IP and proprietary protocols, ensuring interoperability across different system projects. In addition, its firmware is typically designed to facilitate real-time monitoring, diagnostic capabilities and remote configurability, all of which enhance system reliability and operational efficiency.

The JXCP controller is widely used in several fields such as manufacturing, energy management, and building automation. The modular design facilitates the possibilities of use in industrial sectors.

3.3 *Strain sensor*

A strain gauge sensor was employed to measure the force required to deflect the soft actuator. The sensor operates on the principle of detecting material deformation under mechanical load. When a force F is applied, it induces strain in the structure, resulting in a proportional change in length, as described by Hooke's law. This strain leads to a change in the electrical resistance of the strain gauges. An electronic signal conditioning unit (transducer) amplifies this analogy voltage signal and may also process or convert it into a digital format for further analysis.

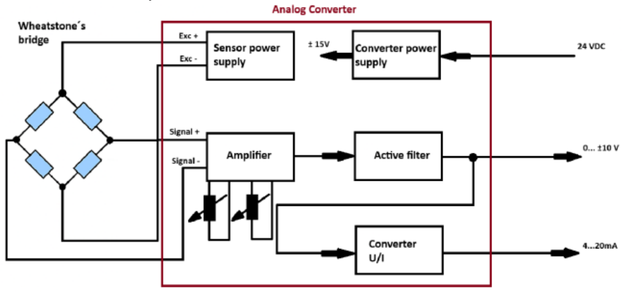

Figure 3. Electric scheme of EMS sensor

EMS21-U(2-10V)-500N is a type of strain gauge force transducer developed by EMSYST, designed for accurate measurement of tensile and compressive forces up to 500 newtons (N). This transducer incorporates a built-in signal converter that provides a voltage output ranging from 2 to 10 volts, facilitating easy interfacing with various data acquisition and control systems (Figs. 3 and 4).

The sensor exhibits a maximum non-linearity and hysteresis of 0.25% of full scale (F.S.), and a creep (30 minutes) of 0.1% F.S., ensuring high measurement precision and maintains performance with a temperature effect on zero and output of 0.15% F.S. per 10°C, suitable for operation within a compensated temperature range of 0°C to +50°C.

Figure 4. 3D model of MEMS sensor

3.4 Soft actuator

The soft actuators analysed in this paper are inspired by biological systems, using internal cavities that inflate or deflate to produce controlled deformation, enabling complex movements like those of living organisms, such as cephalopod tentacles [Cakurda 2024]. Made from flexible materials like silicones and elastomers, these actuators can withstand significant deformation without damage (Fig. 5), enhancing their durability and reliability [Sokolov 2023]. Integrated sensors—typically pressure or tactile—provide feedback on the actuator’s shape and interaction with its surroundings, allowing for proprioception and autonomous operation [Cakurda 2022]. Their geometry varies, with cylindrical or segmented designs that support movements like bending, stretching, or twisting, with segmented forms offering greater motion versatility [Trojanova 2022a]. Control is often achieved using machine learning, particularly deep learning methods such as LSTMs, which process sensor data and predict optimal movement. Altogether, these design and control features enable soft actuators to perform complex tasks with high adaptability and effective environmental interaction across various applications [Trojanova 2022b].

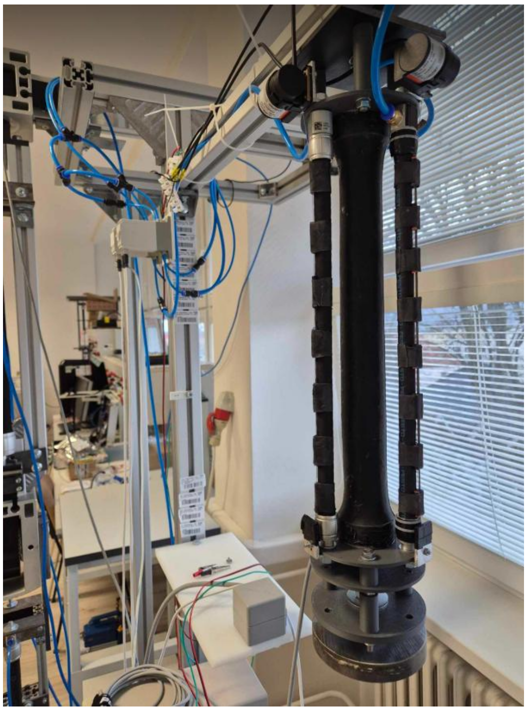

Figure 5. Laboratory soft actuator system

3.5 Model of the experimental construction solution

Included 3d CAD model shows the location of the devices and sensors as they are positioned in relation to each other (Fig. 6). The basic design solution is to place the sensor between the linear axis and the soft actuator. When the linear axis tries to push the soft actuator sideways the sensor will record the magnitude of the force acting on it, and it will also sense the pressure from the side of the actuator as it resists that force.

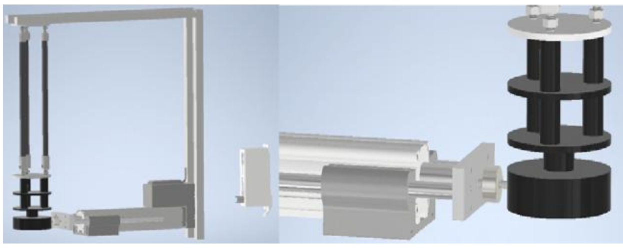

Figure 6. 3D CAD model of construction structure

4 DESIGN OF CONTROL SYSTEM FOR MEASURING THE STIFFNESS OF SOFT ACTUATORS

In order to control the displacement of the linear axis in experiments aimed at measuring the stiffness of soft actuators, a control system based on the Schneider M241CEC programmable logic controller (PLC) was designed. This model in standard configuration contains 14 digital inputs, 10 digital outputs and 2 configurable analogue inputs/outputs, which are used to acquire and process the analogue signal from an EMS21-U type force transducer (range 2-10 V, maximum force 500 N) [Duhancik 2024].

Based on the predefined target position of the linear axis displacement, the control system generates an output signal, or information about the desired industrial Ethernet/IP communication link, which is transmitted to the linear actuator control unit (Fig. 7). The latter then sends electrical impulses to the stepper motor coils, thereby initiating the rotation of its shaft and ensuring that the working element moves to the desired position.

Figure 7. Schneider M241CEC

Accuracy and repeatability of movement are controlled by an integrated position sensor - in this case an absolute encoder, which provides feedback on the current shaft position (Fig. 8). This feedback makes it possible to ensure high accuracy in achieving the desired position, which is essential to ensure the reliability and relevance of experimental measurements and results.

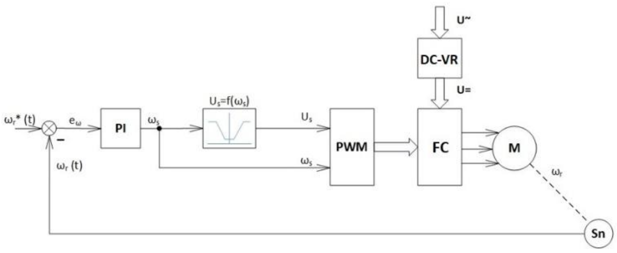

Figure 8. Block diagram of stepper motor control

The measurement algorithm is initiated by an external control signal, which can be generated either by a physical digital input (e.g., a switch or sensor) or by a virtual signal entered via the user interface on the HMI touch panel. When the input signal is activated, the actual values of the linear axis position and applied force are read from the sensor, and these values are then defined as the initial (zero) reference values for the measurement.

The following data processing is realized by means of an evaluation algorithm (Fig. 9) implemented in a programmable logic unit (PLC) designed based on a predefined control structure. The algorithm ensures the control of the sequential measurement procedure, including the precise synchronization of the individual system activities such as motion control, readout of quantities and state evaluation [Duhancik 2022].

The key function of the algorithm is to calculate the basic stiffness parameters of the soft actuator. This is implemented on the base of the recorded values of the applied force when a defined distance is reached. The measurement is carried out under precisely defined pressure conditions of the individual actuator segments, thus ensuring repeatability and consistency of results [Majernik 2021].

The advantage of this system is the ability to perform accurate and reproducible experimental measurements of the mechanical properties of soft actuators that meet the requirements of modern mechatronic applications, especially in the areas of robotics, adaptive manipulators and intelligent automation.

The logical structure of the control process and the individual steps of the algorithm are clearly illustrated in the form of a flow chart, which is shown in Fig. 9. This diagram provides a comprehensive view of the individual phases of the measurement cycle and facilitates the analysis, debugging and possible extension of the control algorithm in the future.

Information on current and achieved position values, applied force, system operating parameters as well as the measurement progress over time is visualized via the Schneider Electric HMIST6400 industrial graphical touch panel (Fig. 10). This HMI panel enables interactive display of data in real time, with measured quantities presented in the form of clear graphical waveforms, numerical values and system status indicators.

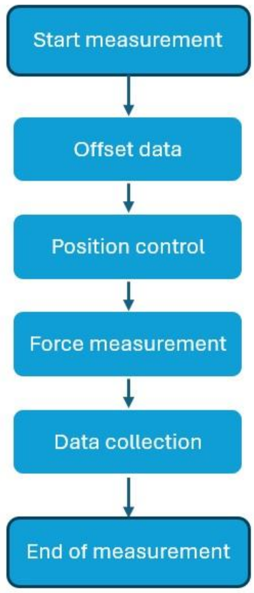

Figure 9. Flowchart of measurement process control

Figure 10. HMIST6400 by Schneider Electric

Such visualization provides the operator or researcher with an immediate overview of the system status and the progress of the experiment, which significantly contributes to a more efficient evaluation of the acquired data. Based on this information, it is possible to promptly identify deviations from the desired values, analyse the behaviour of the system in different regimes and, if necessary, adjust the input operating parameters (e.g., pressure, displacement rate, actuation conditions) to optimise the results [Husar 2018].

In addition, the panel supports the possibility of storing the measured data in internal or external storage, which allows later detailed analysis, archiving of the results and possible integration into higher-level data acquisition and processing systems (e.g., SCADA or MES). Due to its robust industrial design, the panel is also suitable for more demanding operating conditions, thus increasing the overall reliability and usability of the designed system.

5 CONCLUSIONS

By measuring the force required to deflect these actuators, we can improve their design and functionality, leading to improved performance in a variety of applications. By conducting experiment using this design on soft actuators, accurate movements can be achieved with fewer control parameters than currently set on the measured assembly, thus improving reliability and functionality under different operating conditions. The implications of this force measurement can have significant implications for future design changes in a given soft actuator as advances in silicone diaphragm manufacturing provide the basis for the development of robust soft actuators with demonstrably low power consumption while maintaining high flow rates and efficient load response. With this design and control design to measure soft actuator deflection, understanding the mechanical forces involved in actuation accuracy is critical. The force measurement experiment not only provides information for the design process but also increases the predictability of soft actuator performance in a variety of applications. The predicted knowledge gained opens the way to optimizing factors such as spacing, preload, and configuration to achieve desired actuation characteristics while minimizing undesirable effects.

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