

Thermally-Resilient Soft Gripper for On-Orbit Operations

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Abstract—Research in soft manipulators has significantly enhanced object grasping capabilities, thanks to their adaptability to various shapes and sizes. Applying this technology to on-orbit servicing, especially during the capture and containment stages of active space debris removal missions, might offer a secure, adaptable, and cost-effective solution compared to the trend of increasing the degrees of freedom and complexity of the manipulator (e.g. ClearSpace, Astroscale). This work aims to conduct an experimental proof of concept, for which challenges such as radiation, vacuum, and microgravity are significant, but the predominant issue is ensuring effective operation in the extreme temperature swings, where flexible materials may exhibit cryogenic crystallization or drastic shifts in their elasticity. This work addresses this challenge through an initial stage of analytical modeling of the thermal dynamics inside the manipulator in orbit; which is then used for the development of a first multi-layered experimental prototype (leveraging the properties of TPU, silicone, PTFE and aerogel) tested with liquid nitrogen and heat guns. The tendon-actuated servo-driven gripper is tested in the laboratory by varying the shape and size of objects during the grasping. The results, based on servomotor force metrics to assess the flexible manipulator’s adaptability and object capture efficiency across temperature changes, affirm the concept’s viability. Forces increase up to 220% in cryogenic conditions and decrease by no more than 50% at high temperatures.

Index Terms: Space Robotics, Soft Manipulator, Extreme Environment, Space Debris, Thermal Design

I. INTRODUCTION

SPACE exploration has always pushed the boundaries of technology, with robots playing an increasingly vital role. Historically, space robots have been rigid in structure. While these rigid robots have proven effective in many missions, their limitations become evident in challenging terrains, as seen with the Spirit rover, which encountered difficulties in loose soil [1].

In contrast, soft robots, typically crafted from materials with a Young’s modulus under 1 GPa, present numerous advantages. They offer more flexibility and degrees of freedom, which enhances their adaptability to diverse space environments [2]. Notably, soft robots can better manage collisions, minimizing damage and thus outperforming rigid counterparts in specific scenarios. Flexibility in space technology has already been explored in various forms, such as deployable solar arrays [3] and inflatable space modules [4], among others [5].

Recent proposals have introduced innovative concepts of soft robots for space exploration [6], including deployable



Fig. 1. Thermally-resilient soft manipulator proof of concept designed for active space debris removal missions in Low Earth Orbit (LEO).

Mars rovers [7], satellite grippers [8], and others. Although these concepts harness adaptability suitable for varied space missions, the extreme operational conditions in space environments pose challenges. The development of space-ready soft robots is still in early stages. For example, the silicone-based satellite gripper in [8] might face severe challenges in the low temperatures of a LEO orbit. Even higher TRL concepts, some trialed on the ISS such as the gecko-inspired gripper [9], recognize temperature adaptation as a key hurdle for prototypes.

To develop space-qualified soft robotics, it’s vital to bridge the gap between robotics, materials engineering, and cryogenics. Teflon (PTFE), known for its broad temperature range (-260°C to 250°C), has been foundational in space-related components due to its thermal properties [10], [11]. However, most materials used in soft robotics are not suitable for space because of their thermal limitations, making the study of elastomers an ongoing field. Silicones, for example, can resist crystallization even at -120°C [12], and their behavior at elevated temperatures is well-understood [13]. TPU’s performance in frigid conditions is under investigation [14], with an operational range between -90°C and 130°C [15]. Aerogels demonstrate excellent thermal endurance [16], though they may become brittle in certain configurations. Molybdenum grease is renowned as an optimal cryogenic lubricant [17].

Addressing the aforementioned challenges is paramount due to the impact that space-qualified soft manipulators can have on the pressing issue of space debris. Initially conceived

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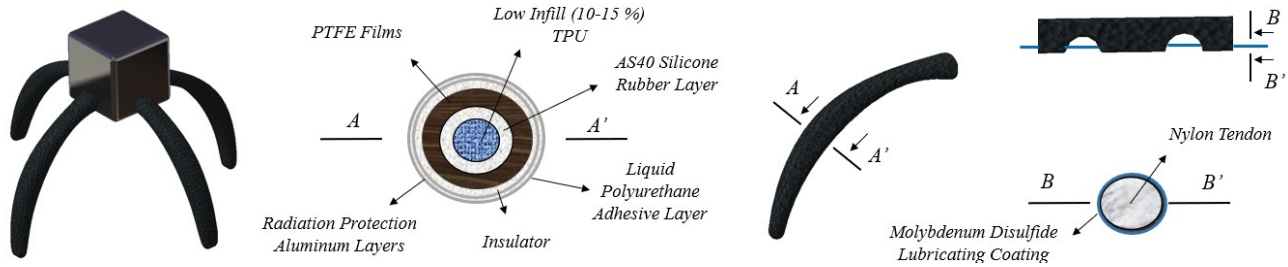


Fig. 2. Cross-sectional view of the multi-layered soft gripper design, detailing each specific layer's material.

in the 1980s for satellite servicing [18], space manipulators have now become essential for debris removal. The first active debris removal mission is scheduled for 2025, a collaboration between ESA and ClearSpace [19]. Currently, there are around 20,000 large debris pieces in Low Earth Orbit (LEO) [20], along with numerous smaller fragments, posing a significant collision threat. Large satellites in LEO face a yearly 0.01% collision risk with sizable debris, a percentage that increases with smaller debris. Such impacts can multiply the debris count, exemplifying the Kessler Syndrome and threatening the future of space exploration.

Efforts to address this problem have been varied, involving not only active debris removal with robotic arms [18], but also large nets [21], tether systems [22], laser ablation [23], and magnetic methods [24]. Drag devices aim to expedite debris re-entry into Earth's atmosphere. Recent research emphasizes the potential of soft robotic manipulators for active debris removal, such as Stanford's gecko-inspired method leveraging adhesive qualities [9], [25], and other proposed soft robotic manipulators [26], [27], though extreme conditions remain a major challenge [6].

This work uses experiments with liquid nitrogen to simulate cryogenic conditions and heat guns to replicate high temperatures, providing insights into material behavior under these extremes. The development of a soft gripper for space debris removal in LEO orbits is guided by these findings. The gripper's multi-layered structure includes thermoplastic polyurethane for flexibility, silicone rubber for support, PTFE (Teflon) for thermal resistance, and aerogel for insulation. A tendon-driven system, made of nylon and lubricated with molybdenum disulfide, ensures functionality in freezing conditions, demonstrating consistent performance across temperatures from -180°C to 220°C .

The article is structured as follows: Section 2 discusses the challenges of operating soft robots in orbit. Section 3 covers the thermal modeling of the system. Section 4 presents the high-level design of the manipulator. Section 5 simulates and optimizes the multi-layered design. Section 6 describes the experimental setup and analyzes the results. The paper concludes with Section 7, highlighting the potential impact of the proposed manipulator on space debris removal efforts.

II. PROBLEM STATEMENT

Space debris, including defunct satellites, spent rocket stages, and collision fragments, presents significant risks

due to its unpredictability. This section highlights the key challenges of active debris removal with manipulators.

A. Types and Quantities of Space Debris

Differentiating space debris by size can provide insights into the varying challenges each size group presents. Table I summarizes these categories.

TABLE I
CLASSIFICATION OF SPACE DEBRIS BY SIZE AND SHAPE.

Size	Shape/Description	Quantity
$\geq 10\text{cm}$	Defunct Satellites, Rocket Stages	20,000+
$1\text{cm} - 10\text{cm}$	Smaller Fragments, Bolt, Paint Flecks	500,000+
$\leq 1\text{cm}$	Micro-debris, tiny fragments	100 million+

B. Space Environment and Temperature Challenges

The unique conditions of space, with vacuum and microgravity, significantly affect heat transfer. In Low Earth Orbit (LEO), a spacecraft alternates between 45 minutes of sunlight, where temperatures can reach up to 220°C , and 45 minutes of darkness, dropping to around -200°C . This rapid thermal cycling occurs due to the absence of an atmosphere to retain heat. Designing systems, particularly soft manipulators for space, requires materials that maintain their properties and functions across these extreme temperature variations.

III. THERMAL DYNAMICS MODELING

This section covers heat transfer dynamic modeling within the soft manipulator. This model will be used for simulations that will allow optimizing the layered design, taking into account material constraints.

A. Heat Transfer Modeling in Orbit

In the space environment, conduction is the primary mechanism for heat movement within the manipulator's layers due to molecular agitation. Convection is generally non-existent in the vacuum of space, radiative heat transfer takes precedence. The proposed model considers both conductive and radiative heat transfer in a transient manner. The governing equation for time-dependent conduction in cylindrical coordinates is:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{1}{r} \frac{d}{dr} \left(k \frac{dT}{dr} \right) + q_{\text{radiation}} \quad (1)$$

Where:

- ρ is the material density.
- c_p is the specific heat capacity at constant pressure.

- T is the temperature.
- r is the radial coordinate.
- k is the material thermal conductivity.
- $q_{\text{radiation}}$ represents the heat added or removed due to radiative transfer.

B. Numerical Solution and Discretization

To solve the equation, a finite difference method (FDM) is employed. For the radial derivative, a central difference scheme can be applied:

$$\frac{dT}{dr} \approx \frac{T_{i+1} - T_{i-1}}{2\Delta r} \quad (2)$$

The second radial derivative can be discretized similarly using the central difference scheme, leading to:

$$\frac{d^2T}{dr^2} \approx \frac{T_{i+1} - 2T_i + T_{i-1}}{\Delta r^2} \quad (3)$$

The temporal discretization can be achieved using a forward difference for the time derivative:

$$\frac{\partial T}{\partial t} \approx \frac{T_i^{n+1} - T_i^n}{\Delta t} \quad (4)$$

Where n is the time step index.

The stability of the numerical solution is crucial. In this context, the CFL condition dictates the relationship between the time step Δt and the spatial step Δr to ensure a stable and accurate solution:

$$\alpha \frac{\Delta t}{(\Delta r)^2} \leq \frac{1}{2} \quad (5)$$

where α is the thermal diffusivity.

C. LEO Orbit Properties

The soft manipulator is designed for operations in a Low Earth Orbit (LEO). The properties of this orbit, typical for LEO altitudes, are summarized in Table II. It's noteworthy that the radiation value provided is an approximation of the radiation received in the LEO orbit.

TABLE II
PROPERTIES OF THE LEO ORBIT

Parameter	Value
Orbit Altitude	160 km - 2,000 km
Orbit Duration	90 minutes
Time in Sunlight	45 minutes
Time in Shadow	45 minutes
Radiation Value (Approx.)	$q_{\text{rad}} = 1460 \text{ W/m}^2$

IV. HIGH-LEVEL SOFT MANIPULATOR DESIGN

This section introduces the high-level design of the soft gripper and the proposed materials, which will be simulated and optimized in Section V. Figure 2 offers an in-depth illustration of the gripper's design, including a cross-sectional view that highlights the various materials used.

A. Material Selection and Multi-Layered Approach

The designed gripper utilizes a multi-layered structure:

- **Inner Layer (TPU):** Thermoplastic polyurethane (TPU) is chosen due to its lightweight and flexibility, especially at low infill rates of 10-15%. However, its use throughout the entire manipulator is restricted since it weakens considerably at high temperatures and becomes brittle at extreme lows. Positioned at the core, it remains shielded from the most drastic temperature swings in space.
- **Intermediate Structural Layer (Silicone):** Silicone has a lower crystallization limit than TPU and, as an elastomer, adds critical structural integrity. The combination with TPU allows to minimize inherent vibrations observed in silicone.
- **External Thermal Stability Layer (PTFE):** PTFE, known for its minimal elasticity variations (around 10%) across a wide temperature range (-200°C to 220°C), is selected for the external layer. While it's not ideal for the entirety of the gripper due to its higher modulus of elasticity at room temperature, its thermal stability makes it apt as an external layer to provide thermal resilience, especially at low infill rates of 25-30%.
- **Thermal Insulation Layer:** A thin layer of flexible aerogel is introduced for its superior insulation properties, acting as a buffer to shield the manipulator's internals from extreme temperatures.
- **Protective and adhesion films:** The outermost layer is made of reflective aluminum, which can reduce radiation effects. Finally, liquid polyurethane enhances the gripper's bond with the object, ensuring a firm grip and minimizing the risk of slip during operations.

This multi-layered approach strategically combines the advantages of each material to produce a gripper that's both functional and durable in the challenging space environment.

B. Manufacturing Process of the Soft Gripper and Actuation

The fabrication of the soft gripper is a multi-step procedure. Each step is detailed below and further detailed in the Supplementary Material:

- 1) **TPU Layer Creation:** The initial layer, made from Thermoplastic Polyurethane (TPU), is produced using Fused Deposition Modeling (FDM) 3D printing at low infill rates.
- 2) **Silicone Layer Formation:** A mold, which can be 3D printed, is employed to shape the subsequent silicone layer. AS40 silicone rubber is mixed with a catalyst to initiate curing. Once poured into the mold, it's left to cure for a duration of 4-6 hours.
- 3) **PTFE Layer Attachment:** Pure PTFE fabrication remains a challenge, primarily due to its high melting point. While some experimental endeavors have made headway in 3D printing PTFE, these methods are still not robust. Other techniques, such as cold molding and sintering, are complex and less feasible for the present

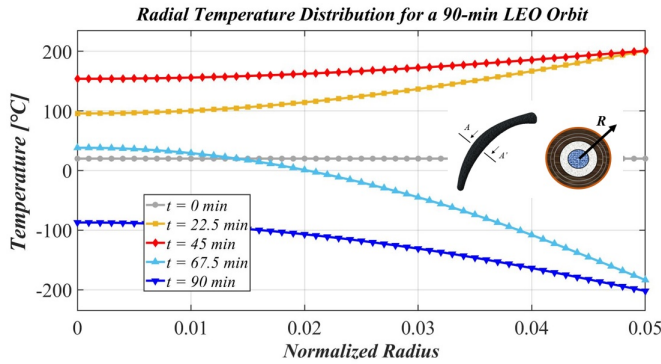


Fig. 3. Simulated temperature evolution along the radius of the final soft gripper design during a complete LEO orbit cycle. The curves depict thermal fluctuations at various time points as the manipulator transitions between sunlight and shadowed regions of the orbit.

purpose. To leverage the beneficial thermal properties of PTFE (Teflon) in this study, thin sheets consisting of 70% PTFE and 30% PETG are used. These sheets are layered onto the soft gripper to form the required thermal resilient shell.

- 4) **Aerogel Insulation:** The aerogel is applied as thin membranes, ensuring uniform coverage and offering thermal insulation properties.
- 5) **Aluminum Film and Coating:** A thin reflective aluminum paper film is adhered to the surface of the gripper to offer protection against radiation. The adhesive layer, ensuring grip with space debris, is applied using a brush.

The actuation mechanism is shown in Figure 2. It is tendon-actuated, servo-driven using nylon from fishing lines. Nylon tendons maintain robustness over a wide range of temperatures. For smooth operation in cold conditions, a coating of molybdenum disulfide grease is applied using a brush for lubrication.

V. MODEL RESULTS AND FINAL DESIGN

The design criterion is that each material layer remains at a safety factor of 1.2 away from its critical crystallization temperature and its melting point. This leads to the analytical result shown in Table III. For these simulations, a simplification of constant diameter in the gripper corresponding to 10cm, consistent with the following experimental prototype, was used. The iterative process produced temperature profiles (Figures 3 and 4). It is observed that the thickest layer is made of Teflon, which will reduce the manipulator’s flexibility in exchange for maintaining temperature resistance.

TABLE III

THERMAL PROPERTIES AND DESIGN CHOICES OF MATERIALS USED IN THE SOFT MANIPULATOR

Material	Heat Coeff k	Density ρ	Specific Heat c_p	Layer
TPU	0.22 W/m·K	120 kg/m ³	1.2 J/g·K	26 %
Silicone	0.2 W/m·K	970 kg/m ³	1.5 J/g·K	23 %
PTFE	0.18 W/m·K	660 kg/m ³	1.0 J/g·K	32 %
Aerogel	0.02 W/m·K	200 kg/m ³	1.0 J/g·K	19 %

Soft Gripper Cross-Sections Temperature Maps

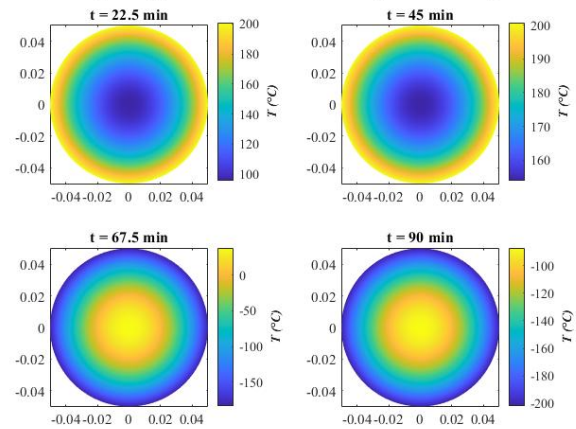


Fig. 4. Simulated cross-sectional temperature maps for the final design of the soft gripper at distinct moments during its LEO orbit cycle. The visualizations emphasize the temperature gradients within the structure.

Moreover, thermal modeling offers key insights into the behavior of the soft manipulator under space conditions:

- 1) The radial temperature profile (Figure 3) exhibits pronounced variations. The external surface encounters temperatures fluctuating from 205°C during sunlight exposure to a chilling -197°C when in the shadow.
- 2) Internally, the gripper experiences a milder temperature swing, with values oscillating between 153°C and -96°C.
- 3) The observations highlight the crucial significance of the thermal design, proving its functionality across diverse thermal conditions.

VI. EXPERIMENTAL PROTOTYPE

This section describes the experiments conducted to test the performance, flexibility, and response of the soft manipulator under different temperature conditions.

A. Test Bench and Instrumentation

Figure 5 illustrates the test bench setup, which includes:

- A robust bar structure to anchor the soft manipulator.
- A Dewar tank filled with liquid nitrogen maintained at -196°C. Immersion of the gripper into this liquid nitrogen can lower temperatures to approximately -180°C.
- A heat gun capable of reaching temperatures up to 220°C or even higher.
- A Type-T thermocouple, chosen for its accuracy in monitoring different ranges of temperatures.
- The high-torque Hitec D950TW servos, utilized to regulate the force applied by the manipulator’s tendons.

B. Manipulator Configurations and Adaptability

The versatility of the soft manipulator was tested through its ability to handle different debris types (Figure 6). Note that the objects used for the tests have reduced mass, since

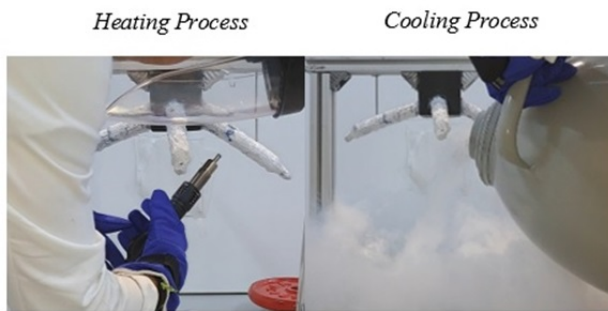
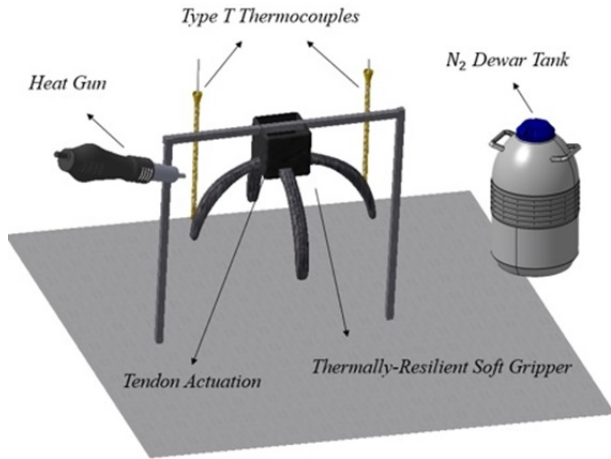


Fig. 5. Test bench setup: manipulator, sensing, and temperature actuators (liquid nitrogen and heat guns).

in microgravity conditions the weight force is negligible (although not the inertia).

- **Dual Arm Configuration:** Using just two of its arms, this setup is suitable for simpler debris (such as complete satellite elements with regular shapes, or small rocket stages), ensuring a firm grasp.
- **Quad Arm Configuration:** By using all four arms, this setup is designed for irregularly shaped debris (as loose fragments or pieces in orbit after collisions), in which the previous configuration may not be sufficient and cause the object to slide laterally, something essential to avoid in space in microgravity conditions due to the energy expenditure that would be required to recover its position. This configuration provides greater stability and control.

Table IV shows the evolution of the servomotor force based on object shape and gripper configuration (dual or quad arm). While the total force required is higher in the quad arm setup, the force per arm decreases significantly for irregular objects due to smaller contact areas. This configuration not only achieves a stable grip with less pressure, enhancing safety in microgravity, but it may also be more energy-efficient.

C. Temperature Variation Performance Metrics and Results

The thermal experiments provide insights into the servo's force requirements across a temperature range. At low temperatures, the required force doubled due to material stiff-

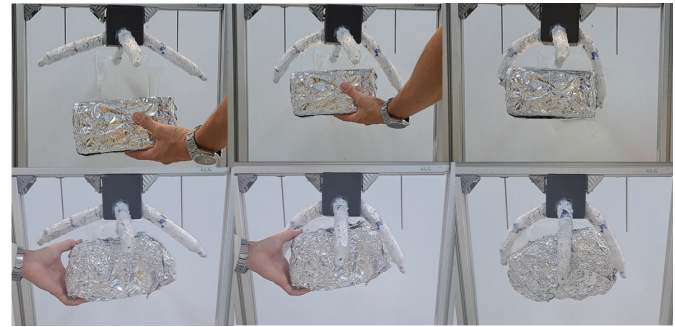


Fig. 6. Demonstration of the soft gripper's versatile gripping capabilities. Top: Dual-arm configuration showcasing the adaptability in handling objects. Bottom: Four-arm approach emphasizing the gripper's enhanced stability and grasp strength when dealing with larger or more cumbersome objects.

TABLE IV
FORCE REQUIREMENTS FOR STABLE GRIPPING OF DIFFERENT DEBRIS AND ARM CONFIGURATIONS.

Debris Shape	Metrics	Dual Arm	Quad Arm
Regular	Total Force (kgcm)	7.8	13.2
	Force per Arm (kgcm)	3.9	3.3
Irregular	Total Force (kgcm)	12.3	14.4
	Force per Arm (kgcm)	6.1	3.6

ening, though this increase would be significantly greater if the gripper were made entirely of silicone, given its tendency to crystallize. As temperatures neared 200°C , the necessary force halved, though this effect could be more pronounced closer to the melting point. Repeated thermal cycling further accentuated these changes: force increased by up to 35% in cold conditions and decreased by 18% in hot conditions, while remaining stable at ambient temperatures.

VII. CONCLUSIONS

This paper presents the experimental proof of concept of a soft gripper tailored for space debris removal in Low Earth Orbit (LEO). The multi-layered design strategically integrates elastomeric materials such as TPU and silicone, which provide flexibility, combined with the thermal stability of PTFE and aerogel insulation.

Notably, the gripper's external surface can experience temperature variations from 205°C to -197°C in LEO orbits, while the design maintains safer internal temperature boundaries. Experimental evaluations highlighted the gripper's ability to grasp objects of diverse shapes, responding effectively to the multifaceted nature of space debris. Observations from the test bench highlighted that at cryogenic temperatures, the servo's force requirements increased due to hardening, while at higher temperatures, the servo became more flexible; both effects intensified with more thermal cycles.

This work has aimed to bridge the gap between soft robotics and space engineering, through pioneering experimentation in this field with liquid nitrogen. Future work will include more extensive experimentation, involving the use of thermal cameras for temperature measurement, tests under vacuum conditions, optimization of the manufacturing

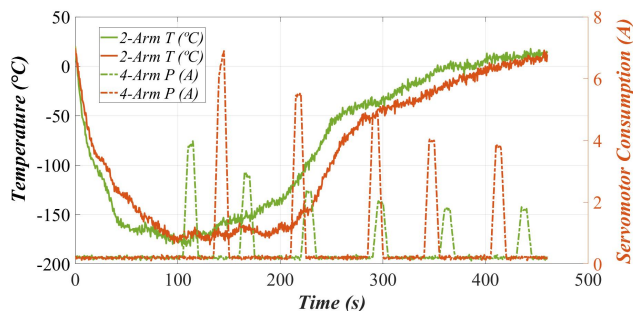


Fig. 7. Experimental results for a temperature cycle (dual arm and quad arm, respectively, under regular debris configuration) showing servomotor consumption in different gripping cases.

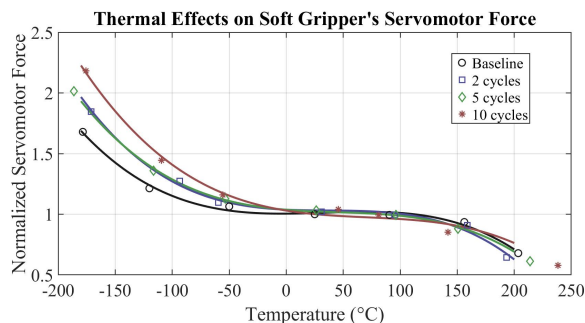


Fig. 8. Servomotor force variation of the soft gripper (dual arm, regular debris shape) with temperature, showing baseline conditions and effects after 2, 5, and 10 thermal cycles.

techniques for the Teflon layer, and improvement of the grasping technique.

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