Proceedings in MANUFACTURING SYSTEMS

Proceedings in Manufacturing Systems, Volume 21, Issue 1, 2026, pp. 9-16 ISSN 2067-9238

DEVELOPMENT OF A TWO-MATERIAL ROBOTIC GRIPPER WITH VARIABLE COMPLIANCE USING ADDITIVE MANUFACTURING

Nefeli ANDREOPOULOU[1] and George-Christopher VOSNIAKOS[2,*]

[1)] MSc Graduate Student, School of Mechanical Engineering, National Technical University of Athens, Athens, Greece
[2)] Prof., Manufacturing Technology Laboratory, School of Mechanical Engineering, National Technical University of Athens, Athens, Greece

https://doi.org/10.5281/zenodo.21821559

Abstract: *A two-material soft robotic gripper based on the Fin Ray Effect is presented. The gripper was developed to combine the shape adaptability of compliant fingers with the structural reliability required for repeated pick-and-place tasks. The design uses thermoplastic polyurethane (TPU) for the deformable finger frame and joints and polylactic acid (PLA) for the crossbeams that guide deformation. A sliding male-female joint was introduced to allow assembly and disassembly without screws or adhesive while maintaining controlled rotational freedom. The gripper is actuated by a lead-screw mechanism that transforms rotation into linear motion and closes (or opens) the two fingers around the object. CAD-based kinematic checks, finite-element simulations for finger deformation checks and prototype tests were used to evaluate the design. The models confirmed the ability of the gripper to handle cylindrical objects up to 60 mm in diameter, weighing up to 400 g, with a maximum targeted gripping force of 8 N. The prototype was fabricated by material-extrusion Additive Manufacturing and was tested with objects of different hardness, mass, shape and sensitivity. The results show that a low-cost, modular two-material Fin Ray gripper can provide practical adaptive grasping while being easy to customize and manufacture.*

Key words: *soft robotics, Fin Ray Effect, additive manufacturing, multi-material gripper; TPU, PLA, finite element analysis.*

1. INTRODUCTION

Robotic grippers are critical end effectors in manipulation tasks ranging from industrial handling to agricultural harvesting and biomedical assistance. Traditional rigid mechanisms provide precision and high load capacity, but they often require accurate object localization and careful force control. When objects are fragile, irregular, or variable in size, rigid contact can concentrate stresses and cause damage. Soft robotics addresses this limitation by exploiting material compliance and geometric deformation as part of the control strategy, thereby enabling safe interaction without a large number of sensors or actuators [1].

Soft grippers are commonly classified according to the mechanism by which the grasp is generated: actuation-based deformation, controlled stiffness and controlled adhesion. Among soft gripper architectures, the Fin Ray Effect has attracted particular interest because it converts lateral loading into a counter-intuitive bending response that wraps around the object. The internal arrangement of the crossbar distributes the force and allows the finger to conform passively to the contact surface [2].

Commercial and research prototypes have demonstrated that this principle can support gentle grasping. However, many implementations remain monolithic, offering limited local tuning of stiffness, limited repairability and relatively little freedom to adapt the same finger architecture to different payloads [3].

This work presents the development of an actuation-based soft gripper that exploits the Fin Ray effect by using different polymer properties where they are most useful. The paper focuses on the design evolution, its numerical verification, the prototype manufacturing and some experimental grasping tests. Its main contribution is the design of the gripper as such and in particular its modularity, enabling variable compliance as well as some adaptability to the shape of the part to be handled.

Section 2 provides a review of the previous relevant work. Section 3 presents the design of the gripper from conceptual to detailed. Section 4 presents numerical simulations partially proving the suitability of the design. Section 5 outlines the manufacturing of the prototype. Section 6 describes testing of the prototype for different parts handled. Section 7 summarizes conclusions and proposes further work.

2. PREVIOUS WORK

In industrial environments, objects may vary in size, geometry, stiffness, surface texture and position. This variability is common in packaging, assembly, sorting, warehouse automation, laboratory automation and small-batch manufacturing. Conventional rigid grippers often require precise object models and accurate alignment, whereas soft grippers can passively conform to uncertain geometries and distribute contact forces over larger areas. Recent review work shows that soft grippers are now being examined not only as biomimetic devices, but

* Corresponding author: Heroon Polytehniou 9, Athens 15773, Greece,
E-mail addresses: *vosniak@central.ntua.gr* (G.-C. Vosniakos), *nefeliandreopoulou@gmail.com* (N. Andreopoulou).

also as practical end-effectors for industrial automation, with attention to actuation, sensing, stiffness control, durability and task integration [4]. Broader surveys of recent gripper technologies also highlight the importance of application-oriented design, where the gripper is developed for a specific manipulation context [5]. This shift is reinforced by more recent reviews that classify soft grippers according to actuation principle, structural design, manufacturing approach and practical use in robotic handling systems [6].

A major class of industrially relevant soft grippers is based on variable-stiffness and multimode grasping. A multimode soft gripper combining a tendon-driven mechanism with layer jamming, allowing the same device to change grasping behaviour and stiffness according to task requirements, is presented in [7]. Pneumatically actuated soft grippers with bistable structures provide another route toward fast and energy-efficient gripping, because bistability can reduce the need for continuous actuation during holding [8]. Reinforced pneumatic designs have also been proposed to resist unwanted out-of-plane bending, which is important in soft fingers [9].

Payload capacity remains one of the major barriers to the industrial use of soft grippers. To address this limitation, high-load bioinspired grippers with force-booster fingers have been developed to combine compliant contact with mechanical amplification of gripping force [10]. Passive conformability is also important, since a gripper may need to adapt to uncertain object geometry. A passively conforming soft robotic gripper with three-dimensional negative stiffness is reported in [11]. Other work has combined dual-mode grasping, stiffness tuning and high load capacity in a single soft gripper [12].

Hybrid gripping mechanisms are another important trend. Electroadhesion is useful for handling thin, smooth, or flexible objects that may be difficult to grasp using purely mechanical fingers [13].

Reconfigurable workspace soft grippers extend the same industrial logic by allowing one device to adapt its grasping configuration to different objects and manipulation tasks [14].

Industrial pick-and-place operations impose strict requirements on speed, repeatability and stability. Variable-stiffness grippers have therefore been investigated specifically for high-speed industrial pick-and-place tasks, where a purely soft structure may deform excessively during acceleration or deceleration [15]. Vacuum-actuated soft robotic finger joints provide another approach to increasing versatility and performance [16]. Reticular origami soft grippers use structured geometry to achieve shape-adaptive and bistable rapid grasping [17].

Dual-modal hybrid grippers with tuneable contact stiffness further show that robust grasping can be improved by combining different contact mechanisms and stiffness states within the same device [18]. Jamming-based structures, such as honeycomb–Velcro jamming grippers, also demonstrate how soft fingers can transition from compliant to rigid states when higher holding stability is required [19]. As soft grippers move closer to industrial deployment, embedded sensing becomes important, e.g. by multi-degree-of-freedom force sensors [20].

The Fin Ray effect remains particularly relevant to industrial soft gripper design because it provides passive shape adaptation through geometry. Fin Ray-inspired fingers bend toward the contacted object, allowing the gripper to wrap around irregular shapes while distributing contact pressure [21]. Lightweight 3D-printed Fin Ray fingers further show how additive manufacturing can be used to create efficient, adaptive and low-mass gripper structures suitable for rapid prototyping and industrial customization [22].

Additive manufacturing also enables direct integration of sensing and structural functionality. A 3D-printed mechano-optic force sensor for soft robotic grippers, enabled by programmable structural metamaterials, demonstrates how the gripper body itself can contribute to force measurement [23].

Finally, low-cost soft grippers for automated pick-and-place systems show that simpler fabrication approaches remain important for practical deployment in small automation cells and laboratory-scale production systems [24].

Overall, the strongest trends are variable stiffness, multimode grasping, structural optimization, embedded sensing, hybrid adhesion, Fin Ray-inspired compliance and additive manufacturing.

Focusing on Fin Ray grippers, these remain largely mono-material components, limiting the possibility of controlled stiffness gradients and localized functional behavior. Therefore, the development of a two-material 3D-printable low-cost robotic gripper with variable compliance using additive manufacturing addresses a clear gap.

3. GRIPPER DESIGN

3.1. Specifications

The aim is to create a mechanism capable of handling cylindrical (or even irregular) shaped objects with a maximum diameter of approximately 60 mm. It must be able to adapt around the object through controlled deformation of the fingers, without requiring excessive force and without causing damage to the object. The object weight should be up to 400 g, which requires a vertical (lifting) holding force of approximately 4 N, so with a safety factor of 2, a design holding force of up to 8 N. The mechanism must allow easy variation of compliance (< 1 min for change) to quickly adapt to different conditions of use. The materials to be used must combine low cost, ease of 3D printing and durability in use.

3.2. Conceptual design

Following the review outlined in Section 2, the study focuses on the family of Fin Ray-based compliant robotic grippers with fingers, due to the high degree of adaptability and versatility this principle offers.

The main concept is that each finger has relatively flexible wall acting as the deformable “skin”, providing the required flexibility for the Fin Ray Effect, which is reinforced by cross-beams, acting as bones imposing stability and control over the deformation angle. In this

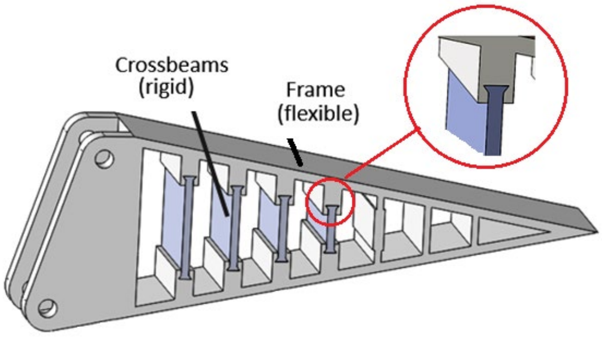

Fig. 1. The finger concept with frame-crossbeam joint detail.

way, in addition to mechanical reinforcement, adaptability is served: by changing the number of crossbeams or their thickness, the stiffness of the gripper can be parameterized.

Two variants centering on crossbeams were considered, namely lattice or solid. The stiffness can be adjusted by varying the material used and, in the former case, the lattice geometry and strut thickness, whereas in the latter case, the thickness of the beams. For reasons of simplicity, solid crossbeams were opted for, see Fig. 1.

The complexity of the joint between the frame and the crossbeam is pinpointed as a main area for detailed design. It has to allow relative rotation of the crossbeam in the frame while also disallowing linear movement and yet ensuring easy replacement for adjusting the compliance of the finger. Conceptually, this joint materialised as a sliding contact with appropriate tolerancing, leveraging the concept of form-based locking instead of using adhesives, screws, pins or other mechanical artefacts see Fig. 1.

3.3. Detailed design

The initial design, providing the baseline for further ramifications, is shown in Fig. 2.

The gripper is designed so that the fingers move symmetrically around a central axis. As the fingers converge, they deform in a controlled manner thanks to the combination of a flexible frame and rigid beams. This deformation allows reliable contact with the object and adaptation even to asymmetrical surfaces, resulting in a

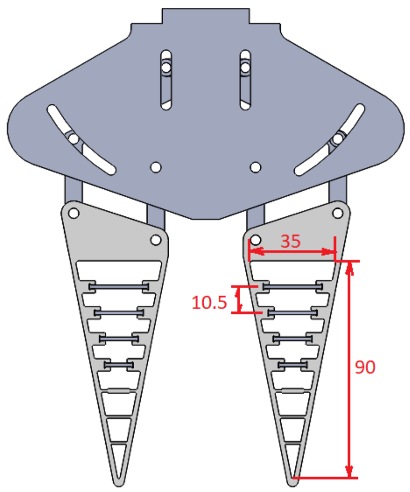

Fig. 2. The initial design of the gripper.

Table 1

Properties of crossbeam candidate materials [25]

Material	UTS (MPa)	Impact strength (KJ/m^2)	Young's modulus (GPa)
PLA	50–65	3–8	3.0–3.8
Tough PLA	45–60	8–20	2.2–3.2
PETG	45–55	5–15	1.8–2.4
ABS	30–45	10–30	1.5–2.2
Nylon	45–75	20–100	1.0–2.0
Polycarbonate	55–75	40–90	2.0–2.6
Glass-reinforced PLA	35–60	3–10	4.5–8.0

passively adaptive mechanism. The thickness of the finger walls (2 mm) was selected to allow deformation without losing elastic recovery.

Regarding the materials to be employed, Thermoplastic polyurethane (TPU) and Polylactic Acid (PLA) were earmarked from the start, according to the combined criteria of mechanical properties, availability for 3D printing and cost. They are both compatible with extrusion based 3D printers, instead of SLA or SLS printers, i.e. a low-cost variant of AM yet offering acceptable quality of build and surface finish for the prototyping application at hand. There were numerous other candidate materials, as depicted in Table 1.

Given the low gripping forces, there does not seem to be a particular issue with PLA, which is also easy to print and inexpensive. If a reduction of the beam thickness is needed, a stiffer material can be used, e.g. Glass-reinforced PLA. Furthermore, if the impact resistance of PLA needs improvement as a result of in-operation performance tests, a 'Tough PLA' grade, as is commercially known, can be opted for.

Similarly, Table 2 presents alternative thermoplastic elastomer materials that may replace TPU for making the frame. Note that in this case, UTS is interpreted as the maximum stress before failure. TPC could be an alternative, but TPU is more common as a 3D printing material, although printing speed is limited and the process window is narrow.

Particular attention was paid to the configuration of the gripper, especially to number of fingers. Although the use of three fingers can provide greater symmetry when contacting objects, the two-finger arrangement significantly simplifies the geometry of the mechanism, reduces the required space and allows for faster construction with a smaller number of components.

In addition, a differentiation was made in the way the crossbeams along the finger are implemented. Specifically, the first four beams, which also accept the highest loads during bending, are made of PLA to

Table 2

Properties of frame candidate materials [26] (NB:No break)

Material	UTS (MPa)	Young's modulus (GPa)	Shore hardnes s
TPU	25-55	0.01-0.10	70A-98A
TPE / TPS / SEBS	5-25	0.005-0.05	30A-85A
TPC/thermoplastic copolyester	25-50	0.03-0.25	90A-55D
PEBA/polyether-block-amide	25-45	0.02-0.12	70A-63D
TPA/flexible polyamide	25-45	0.03-0.20	75A-55D
PCTPE/plasticized copolyamide	30-50	0.05-0.25	80A-95A
Flexible PLA/soft PLA blends	15-35	0.05-0.30	80A-95A

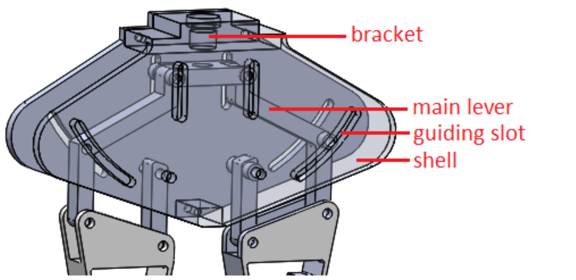

Fig. 3. The 3D model of the shell in a transparent design mode.

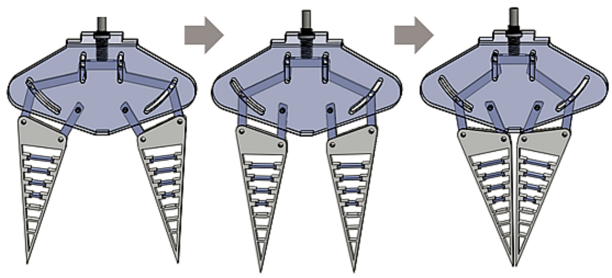

Fig. 4. The final mechanism in characteristic poses.

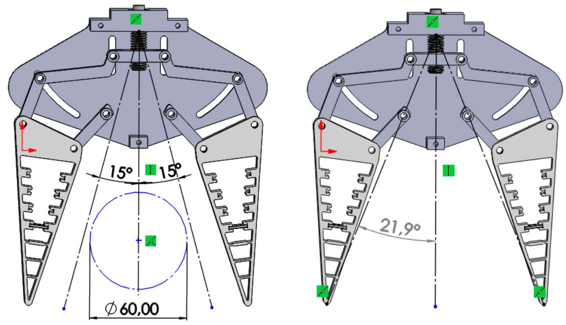

Fig. 5. The opening angle of the mechanism.

provide sufficient rigidity and reinforcement of the Frame. In contrast, the three lower beams are integrated with the Frame, so as to function as part of the flexible body of the finger. This compromise also arose due to spatial constraints: in that area, the distances of the opposite sides of the frame are small and the introduction of additional independent components would not bring a substantial gain in either mechanical behavior or construction time and cost.

The joints between frame and crossbeams were designed to allow controlled rotational movement of the fingers around their axis, while ensuring the required structural integrity of the whole, see Fig. 1.

The housing functions as a guide and stabilizing frame, supporting the mechanism and limiting unwanted deviations during movement, see Fig. 3. Its geometry was formed in an equilibrium position, that is, in an intermediate state accommodating an object with a diameter of approximately 35 mm in the center, where the fingers are neither fully open nor fully closed. This "neutral" position allowed the deformation and behavior of the system to be reliably evaluated in both directions of convergence and divergence of the fingers.

In the kinematic analysis that follows, the joints and the shell were subject to parametric modifications. Observation of their behaviour under operating conditions led to continuous minor changes in the dimensions, aiming to improve operation smoothness.

3.4. Kinematic analysis.

The analysis focused on both the individual behavior of the finger and the cooperation of all parts of the mechanism. The main objectives were: identifying the contact points with the objects, understanding the motion curve and checking the functionality of the mechanism.

To achieve the required kinematics, the actuation mechanism is a lead screw whose rotation is converted into linear translational motion based on the screw's pitch. This displacement is transferred to the fingers through links and pin joints. Initially, a functional design was developed around a cylindrical object with a diameter of 35 mm, as a first reference.

The analysis was carried out in Solidworks™ making use of through constraints, such as concentricity at the imaginary pin points, to ensure purely rotational motion and 'screw mate' between the screw and the bracket.

However, the initial simulation showed erratic movement of the large beams, causing instability and uncontrolled trajectory at the ends. Also, the central support bracket was over-constrained, disallowing the necessary translational freedom. To address both problems, slots were added to the shell. After the design changes, the kinematic analysis confirmed that the gripper can operate stably over a range of objects, see Fig. 4.

As specified, the gripper had to be able to grip objects up to 60 mm in diameter, with an estimated angular variation of each finger in the range of (0–15) °. The results showed a maximum opening angle of 21.9 ° per finger (Fig. 5), potentially accommodating larger parts.

4. SIMULATION OF FINGER DEFORMATIONS

Simulation allows the transition from the level of theoretical design to a first stage of functionality verification, while providing useful data for design improvement. The methodology proceeded in two stages using Solidoworks Simulation™:

- Static Linear Analysis for low loads: It was used as an initial control tool, aiming to quickly verify the validity of the design. Although it cannot accurately describe the phenomena of large deformation, it provides a useful insight into the logical correctness of the geometry and connections.
- Static Non-Linear Analysis for large displacements: Given the large deformations intrinsic in the Fin Ray effect and the use of flexible materials (TPU), it was necessary to transition to non-linear analysis, more realistically representing the contact with objects, stress distribution and deformation evolution.

4.1. Linear analysis for low loads

The purpose was not to produce a fully realistic operating model, but to evaluate multiple configurations fast, to identify key failures such as poor connections, unrealistic contacts, errors in boundary conditions and to verify finger kinematics. The model was setup in Solidworks Simulation™ as follows:

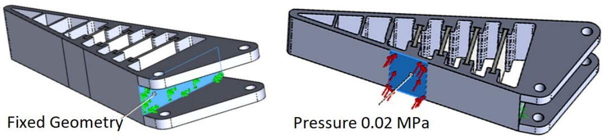

Fig. 6. Boundary conditions and load definition.

A custom material was defined for the TPU used in the frame, based on literature data, with the following key properties: Elastic Modulus = 15 MPa, Poisson's Ratio = 0.48, Density = 1200 kg/m³, Tensile Strength = 30 MPa, Yield Strength = 20 MPa. PLA was chosen for the crossbeams.

Boundary Conditions: The upper plane of the finger was defined as fixed, representing the connection with the rest of the system, see Fig. 6.

Contact Conditions: no penetration was defined at the crossbeam-frame interface. In this way, the crossbeam elements remain in contact with the frame without being "bonded", thereby enabling investigation of possible disconnection during loading.

Distributed pressure was applied on a contact surface of area 20 mm × 20 mm in the middle of the finger, which first comes into contact with the object and from where the deformation starts and subsequently propagates throughout the structure, see Fig. 6.

The load estimation was carried out based on similar studies on Fin Ray gripper type mechanisms [27], [28], where realistic load ranges for compliant gripping applications are:

- (0.02–0.1) MPa for soft objects,
- (0.1–0.5) MPa for objects of medium hardness,
- ≥ 0.5 MPa for hard or heavy objects.

A pressure of 0.02 MPa was chosen as a reference value. When applied to a characteristic contact surface of the finger 20 mm × 20 mm^2 this gives a force of 8 N.

If there was no deformation of the fingers and the holding was done exclusively by friction (worst case scenario), a friction coefficient of 0.5 would be enough to safeguard secure holding of objects weighing 4 N (ignoring inertial forces due to motion). Given the deformation of the fingers, the gripping is now also due to the shape of the deformed finger.

The model provided useful insight, see Fig. 7.

Then, multiple changes were applied to the design, the main modifications applied being (a) a change of dimensions in the frame-crossbeam joint, so that no detachment occurs under load, and at the same time,

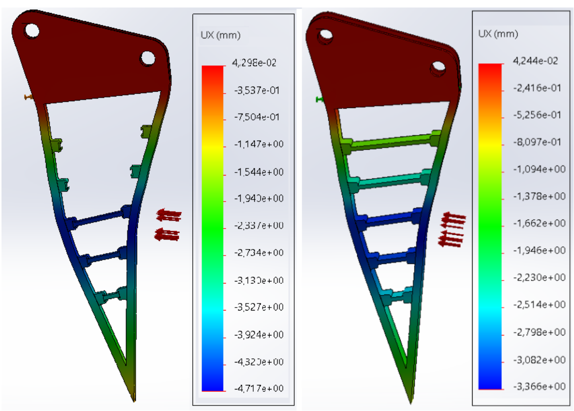

Fig. 7. Preliminary result of linear model for displacement.

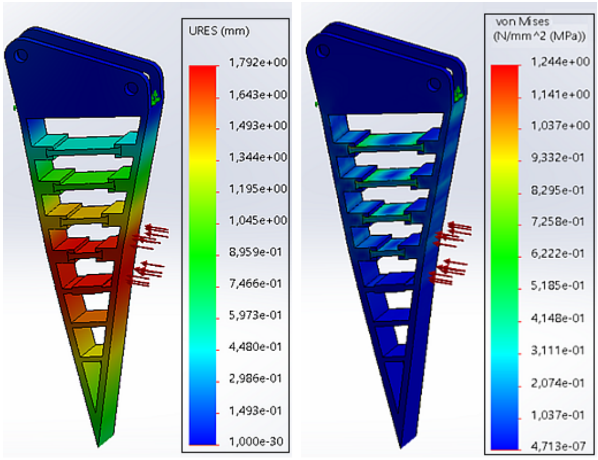

Fig. 8. Indicative results of the final linear analysis model.

finger movement is not restricted and (b) a change of thickness of the TPU frame walls towards a more balanced deformation. Results are shown in Fig. 8.

The following observations were made:

- The overall result appears realistic and normal, with no signs of mechanical failure.
- The displacement in the UX axis is of the order of a few mm, which is expected for the scale of the problem.
- The stresses developed remain very low compared to the strength of both TPU and PLA.
- Stress concentration is observed mainly in the recesses and in the interface of the crossbeams with the frame, consistent with the operation of the device.
- The crossbeams show minimal deformation due to their increased stiffness compared to the frame.
- In the pressure range below 0.05 MPa, the crossbeams maintain the desired mechanical coupling with the frame.

With pressure increase beyond 0.05 MPa, 'Excessive Displacement' is observed, which cannot be correctly handled within a linear static analysis. Thus, a transition to Non-Linear Analysis was tried, where the loads are applied stepwise.

4.2. Non-linear analysis for large displacements

The same methodology that had been used in the linear static analysis of Section 4.1 was applied in this case, too, but with the necessary modifications. In particular, in the SolidWorks Simulation™ settings, Nonlinear Options were activated, using automatic time stepping. The loading was progressively applied divided in 10–20 consecutive steps, with an initial time step of 0.05–0.01, a minimum of 1e^{-5} and a maximum of 0.1. The case studies depicted in Fig. 9 corresponds to a pressure of 0.06 MPa, i.e. a load of approximately 24 N.

It is observed that the distribution of von Mises stress is concentrated mainly in the areas of crossbeam-frame interface. The maximum stress values two orders of magnitudes lower than the strength of both TPU and PLA. This means that, at least in the pressure range studied, neither permanent deformation nor material failure is expected.

Regarding the displacements, the results show an acceptable bending of the finger, with displacement values of the order of tenths of a mm at the tip for a pressure.

Overall, nonlinear analysis confirms that the gripper can operate safely under the predicted conditions, while offering a more accurate estimate of the actual behavior compared to the static analysis.

However, note that the software used encountered convergence problems for pressures larger than 0.6 MPa. For that purpose, use of software specializing in nonlinear analysis is required.

5. PROTOTYPE MANUFACTURING

The Creality™ Ender V3 KE printer and the Creality Print 5.1 software were used to build the prototype. Two materials were used in the form of 1.75 mm filament:

- TPU - eSUN™ TPU-LW Fillament White;
- PLA - eSUN™ ePETG-HS High Speed.

The printer settings are shown in Table 3.

The process did not start immediately with the full printing of the prototype. Instead, a systematic approach was followed, with gradual testing of individual features and components, in order to determine the appropriate tolerances, dimensional compensations (offsets) and the optimal printing settings.

The links were critical as mechanical robustness had to be ensured on the one hand and the ability to assemble/disassemble without excessive force on the other. Specifically:

- Levers and beams: The goal was the appropriate clearance, which would ensure a stable connection during deformation and, at the same time, the ability to disassemble quickly without excessive force. The optimal value was determined to be 0.05 mm. The compensation was applied to the PLA levers and beams, as PLA clearly shows better 3D printing accuracy compared to TPU.
- Holes − Screws: For the holes that accommodate screws or pins, the diameter clearance was +0.1 mm.
- Bearings: for fitting the SKF 618/7 bearing in its pocket, a K6 fit class (slight Interference) was achieved by a 13.99 mm pocket diameter.
- A wall thickness of the TPU frame at 1.5 mm resulted in insufficient layers, especially near the joints. At 2 mm, an ideal balance was achieved.

Table 3

3D printing settings applied (M: monotonic, R: Rectilinear)

Characteristic	Setting	TPU	PLA
Temperature	Nozzle & Extruder (°C)	240	200
	Heatbed (°C)	36	35
Quality	Layer Height (mm)	0.2	0.2
Strength	Bottom Surface Pattern	M	M
	Internal infill Pattern	R	R
	Infill (%)	15	100
	Infill direction (°)	45	45
Support	Type	Tree	Tree
Speed	Initial layer (mm/s)	30	70
	Initial layer infill (mm/s)	105	105
	Outer wall (mm/s)	200	200
	Inner wall (mm/s)	300	300
Printing time	Total (hr)	2.5	7.5

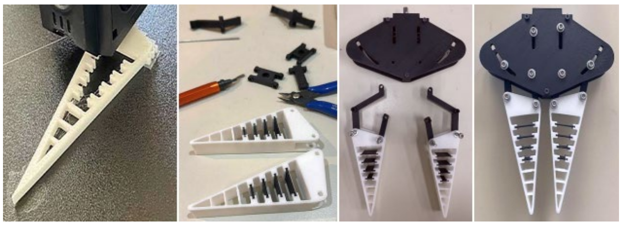

Fig. 9. Prototype manufacturing phases (left to right): frame 3D printing, finger assembly, linkage assembly, assembled gripper.

Note that some steps in the assembly process required machining, e.g., regarding the lead screw fitting into its bracket. Snapshots of the manufacturing process are shown in Fig. 9.

6. TESTING

The testing procedure was designed to evaluate the functionality of the gripper in real-world object handling conditions, focusing on:

- The gripper's ability to grasp objects of different geometries and materials.
- The stability of the object's transfer from one point to another, without slippage or drop.
- The repeatability of the movement and the overall reliability of the construction.

The tests involve 6 different specimens, with different characteristics in terms of the shape, dimensions, weight, hardness and sensitivity (see Fig. 10 and Table 4).

The procedure involves capturing the specimen at a starting position, transporting it for a distance of 30 cm and dropping it onto a receiving receptacle from a distance lower than 2 cm. The transportation and the opening/closing of the fingers to capture/drop the part by turning the leadscrew were done manually.

The tests were recorded on video, which allowed the evaluation of the quality parameters (stability, deformation mode, release mode). Indicative snapshots for specimen 1 are shown in Fig. 11.

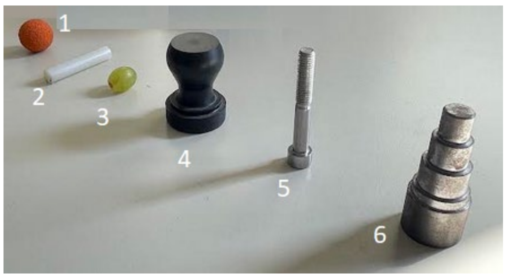

Fig. 10. The set of specimens used for prototype gripper tests.

Table 4

Test specimen characteristics

No	Name	Max diameter (mm)	Weight (g)	Hardness / Sensitivity
1	Sponge sphere	35	4	Soft & deformable
2	Silicon rod	10	10	Relatively hard
3	Raisin	12	8	Soft & sensitive
4	Plastic knob	52	75	Relatively hard
5	Steel screw	17	51	Hard & rigid
6	Steel axle	60	350	Hard & rigid

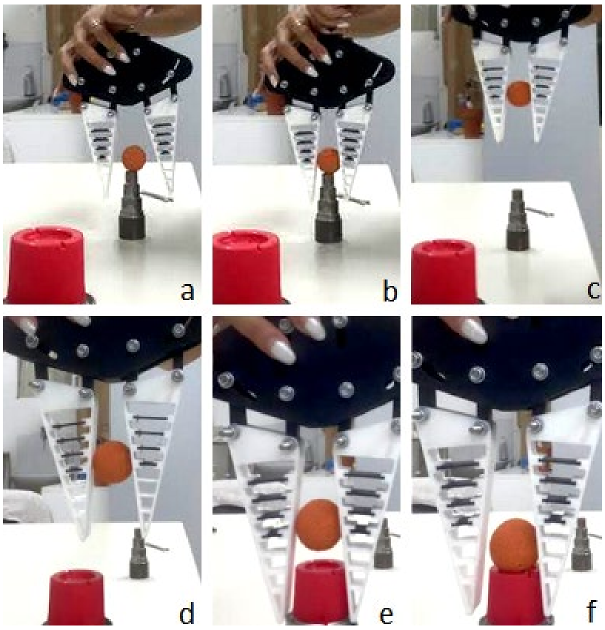

Fig. 11. Test phases Picking (*a*, *b*), Moving (*c*, *d*), Placing (*e*,*f*).

Fig. 12. The gripping of each specimen type.

The process was repeated for all the pieces. The gripping of each of them by the two fingers of the device after their capture is shown in Fig. 12.

The experimental results demonstrated that the gripper is functional and corresponds to the theoretical kinematics simulated in CAD.

Referring to Fig. 12, for soft specimens (e.g. 1), it was observed that the deformation is absorbed by the object itself, while the fingers show lower signs of deformation. However, in tests with harder specimens (e.g., 4−6), the fingers showed the expected flexibility and adaptability, confirming their ability to behave compliantly depending on the load and the nature of the object. Note that the gripper did not cause any kind of damage or injury to the sensitive specimen no 3.

In some cases during the tests, when the center of gravity of the part was well outside the gripper fingers, the parts slipped during transport, due to the bending torque that was created and also due to the smooth surface of the frame, which reduces the coefficient of friction and, by extension, the holding force.

Another issue that emerged concerns the quality of the parts manufactured using AM technology. Minor imperfections in the geometry led to some problems, such as "sticking" of the pins in the notches.

7. CONCLUSIONS AND OUTLOOK

This work aimed to develop a compliant robotic gripper, utilizing the Fin Ray Effect logic and multi-material 3D printing technology. Through the design process, kinematic analysis and FEA simulations, it was verified that the gripper fingers are deformable and able to adapt to objects with a diameter of up to 60 mm, ensuring stable retention for objects weighing up to 400 gr as per original specifications.

The experimental process confirmed the functionality of the mechanism, as the gripper met the theoretical predictions and showed the expected behaviour. Therefore, the main objective set at the beginning of the work were achieved to a satisfactory extent, laying the basis for further development and improvements

Further work is envisaged in the following directions:

- Large deformation behaviour of the fingers should be studied by simulation through the use of appropriate non-linear FEA software.
- Furthermore, it would be important to extend the FEA studies to include grip assessment and evaluation of deformability in objects with more complex geometry, i.e. by applying loads at different points each time.
- Finally, for stability reasons, it would be desirable to extend the design to three-finger grippers following the same methodology laid out in this work.

REFERENCES

[1] B. Tarhan, S. Asif, P. Webb, M. Chacin. *A review of flexible robotic gripping system*, Frontiers in Manufacturing Technology, 5, 2025, 1517727.

[2] J. Shintake, V. Cacucciolo, D. Floreano, H. Shea. *Soft robotic grippers, Advanced Materials*, 30, 29, 2018, 1707035.

[3] W. Crooks, G. Vukasin, M. O'Sullivan, W. Messner, C. Rogers. *Fin Ray Effect inspired soft robotic gripper: From the Robosoft Grand Challenge toward optimization*, Frontiers in Robotics and AI, 3, 2016, 70.

[4] A. Dzedzickis, J. Subačiūtė-Žemaitienė, E. Šutinys, U. Samukaitė-Bubnienė, V. Bučinskas. *Soft grippers in robotics: Progress of last 10 years*, Machines, 12, 2024, 887.

[5] J. Qu, Z. Yu, W. Tang, Y. Xu, B. Mao, K. Zhou. *Advanced technologies and applications of robotic soft grippers*, Advanced Materials Technologies, 9, 2024, 2301004.

[6] Y. Zhang, X. Zhang, Y. Wang, J. Liu. *Soft robotic grippers: A review*, Frontiers in Materials, 12, 2025, 1692206.

[7] B. Fang, F. Sun, L. Wu, F. Liu, X. Wang, H. Huang, W. Huang, H. Liu, L. Wen. *Multimode grasping soft gripper achieved by layer jamming structure and tendon-driven mechanism*, Soft Robotics, 9, 2022, 233–249.

[8] Z. Zhang, X. Ni, H. Wu, M. Sun, G. Bao, H. Wu, S. Jiang. *Pneumatically actuated soft gripper with bistable structures*, Soft Robotics, 9, 2022, 57–71.

[9] H. Li, D. Xie, Y. Xie. *A soft pneumatic gripper with endoskeletons resisting out-of-plane bending*, Actuators, 11, 2022, 246.

[10] H. Li, P. Zhou, S. Zhang, J. Yao, Y. Zhao. *A high-load bioinspired soft gripper with force booster fingers*, Mechanism and Machine Theory, 177, 2022, 105048.

[11] A. H. Chu, A. S. J. Su, R. J. Wood. *A passively conforming soft robotic gripper with three-dimensional negative stiffness*, Soft Robotics, 10, 2023, 651–663.

[12] T. T. Hu, X. J. Lu. *A dual-mode and enclosing soft robotic gripper with stiffness-tunable and high-load capacity*, Sensors and Actuators A: Physical, 354, 2023, 114294.

[13] C. Xiang, Z. Li, F. Wang, Y. Guan, W. Zhou. *A 3D printed flexible electroadhesion gripper*, Sensors and Actuators A: Physical, 363, 2023, 114675.

[14] S. Jain, S. Dontu, J. E. M. Teoh, P. V. Y. Alvarado. *A multimodal, reconfigurable workspace soft gripper for advanced grasping tasks*, Soft Robotics, 10, 2023, 527–544.

[15] M. Zhu, A. N. K. Nasir, G. Alici, R. Mutlu. *Robust grasping of a variable stiffness soft gripper in high-speed industrial pick-and-place task*s, Soft Robotics, 11, 2024, 888–900.

[16] C. W. Ou Yang, S. C. Low, J. E. M. Teoh, P. V. Y. Alvarado. *Enhancing the versatility and performance of soft robotic grippers with vacuum-actuated soft robotic finger joints*, Soft Robotics, 11, 2024, 901–915.

[17] N. Hou, M. Wu, Q. Zhao, Z. Tang, K. Wang, X. Xu, X. Zheng, G. Xie. *Reticular origami soft robotic gripper for shape-adaptive and bistable rapid grasping*, Soft Robotics, 11, 2024, 550–560.

[18] J. Zhu, Y. Zhang, Y. Wang, X. Liu, H. Xu. *A dual-modal hybrid gripper with wide tunable contact stiffness for robust grasping*, Soft Robotics, 11, 2024, 916–930.

[19] Y. C. Chung, Y. H. Lee, H. S. Kim. *Soft robotic honeycomb-Velcro jamming gripper design*, Actuators, 13, 2024, 359.

[20] H. Mun, D. S. D. Cortes, J. H. Youn, K. U. Kyung. *Multi-degree-of-freedom force sensor incorporated into soft robotic gripper for improved grasping stability*, Soft Robotics, 11, 2024, 628–638.

[21] J. Yao, Y. Fang, X. Yang, P. Wang, L. Li. *Design optimization of soft robotic fingers biologically inspired by the Fin Ray effect with intrinsic force sensing*, Mechanism and Machine Theory, 191, 2024, 105472.

[22] G. L. Srinivas, P. S. Rao, K. S. Reddy. *Versatile 3D-printed Fin Ray effect soft robotic fingers*, Journal of the Brazilian Society of Mechanical Sciences and Engineering, 46, 2024, 570.

[23] C. Hegde, R. C. Mysa, A. Chooi, S. Dontu, J. M. R. Tan, L. H. Wong, P. Valdivia y Alvarado, S. Magdassi. *3D-printed mechano-optic force sensor for soft robotic gripper enabled by programmable structural metamaterials*, Advanced Intelligent Systems, 6, 2024, 2400057.

[24] M. S. Demirsoy, M. E. Atalay, A. Bilurdagi, M. Ç. Kutlu. *A low-cost soft gripper for automated pick-and-place systems*, Journal of Smart Systems Research, 5, 2024, 33–39.

[25] M.Algarni, S. Ghazali. *Comparative Study of the Sensitivity of PLA, ABS, PEEK, and PETG's Mechanical Properties to FDM Printing Process Parameters*. Crystals, 11(8), 2021, 995.

[26] M. León-Calero, S.C. Reyburn Valés, Á. Marcos-Fernández, J. Rodríguez-Hernandez. *3D Printing of Thermoplastic Elastomers: Role of the Chemical Composition and Printing Parameters in the Production of Parts with Controlled Energy Absorption and Damping Capacity*. Polymers, 13(20), 2021, 3551.

[27] M.S. Sofla, H. Golshanian, E.I. Sklar, M. Calisti. *Modeling and modification of fin-ray effect grippers to improve their load capacity and grasp stability*. Sensors and Actuators A: Physical, 392, 2025, 116711.

[28] X. Shan, L. Birglen. *Modeling and analysis of soft robotic fingers using the fin ray effect*. The International journal of robotics research, 39(14), 2020, 1686-1705.