Metamaterial-based soft grippers for harvesting fragile crops

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Abstract – **Robot-assisted harvesting of delicate fruits is a technological challenge due to the contradictory requirements on robotic grippers that must deliver conformal grasping and versatile plucking without damaging the crops. To address this problem, we propose a robotic gripper with two extended fingers and a removable metamaterial layer, the topological structure of which is optimized for a proper balance between stiff and soft behavior and advanced conformability to diverse fruit shapes. We prove the advanced grasping functionality of the gripper numerically and experimentally by handling truss tomatoes.**

I. Introduction

Agricultural products have always been essential worldwide and nowadays the demand for them continuously grows due to the ever-increasing human population. However, labor shortages and the lack of robotization in harvesting high-quality crops have complicated efforts to maintain and boost production speed as most of these crops are still handled and harvested by hand. For instance, tomatoes are delicate products that require careful manipulation during harvesting and packaging to maintain the high-quality standards imposed by the fresh vegetable market.

The harvesting of tomatoes can potentially be automated by using robots with a built-in vision system enabling them to identify ripe crops. However, it also requires solving the quest of selecting proper robotic grippers, which should neither be too rigid to prevent damage nor too soft to enable plucking tomatoes from the plant. This study aims to develop grippers that can ensure a soft grasp without compromising the integrity of tomatoes and have sufficient stiffness for plucking.

The existing gripper designs suffer from three major classes of problems. First, the achievable gripping force may be too low for the plucking applications. Second, many designs are aimed at linear motion while plucking involves rotation. Finally, designs with integrated sensory and/or algorithmic control are often too expensive to manufacture and maintain [1, 3]. We search for a promising solution in metamaterials that have already demonstrated their shape-morphing potential [4] and the ability to deal with delicate objects without sensory feedback [2].

II. Design of a metamaterial-based gripper

We constructed an electrically actuated gripper that can secure a grasp through two actuated motions – opening with a spring and closing with a cable. The final concept shown in Fig. 1a includes two extended fingers with two perpendicular attachments that increase the contact area with a tomato. The rigid bases of the fingers, with a stiff behavior, are covered by a layer of soft metamaterial with a shape-morphing property.

The suitable topology for the metamaterial layer was identified numerically by solving a contact problem for conventional (positive Poisson's ratio), re-entrant auxetic, and achiral (negative Poisson's ratio) metamaterial topologies and estimating the contact pressure distribution and resistance to shear. To ensure sufficient flexibility, we considered 3D-printed SLA Flexible 80, SLS EPU 40, and FDM TPU with hyperelastic behavior as constituent materials for the metamaterial layer (Fig. 1b). We analyzed a simplified tomato-plucking process that includes compression (up to 50 N) and shear (up to 50 N) by excluding slip and twist as less relevant.

The analysis of the compression load case showed that the achiral metamaterial delivers the most uniform pressure distribution that was unified further by considering the shear load and optimizing the geometric parameters of the unit cells. The final design of the metamaterial layer (Fig. 1a) delivers the contact pressure shown in Figs. 1c-d for the SLA Flexible 80A metamaterial that allows the preservation of the integrity of classic and cherry tomatoes.

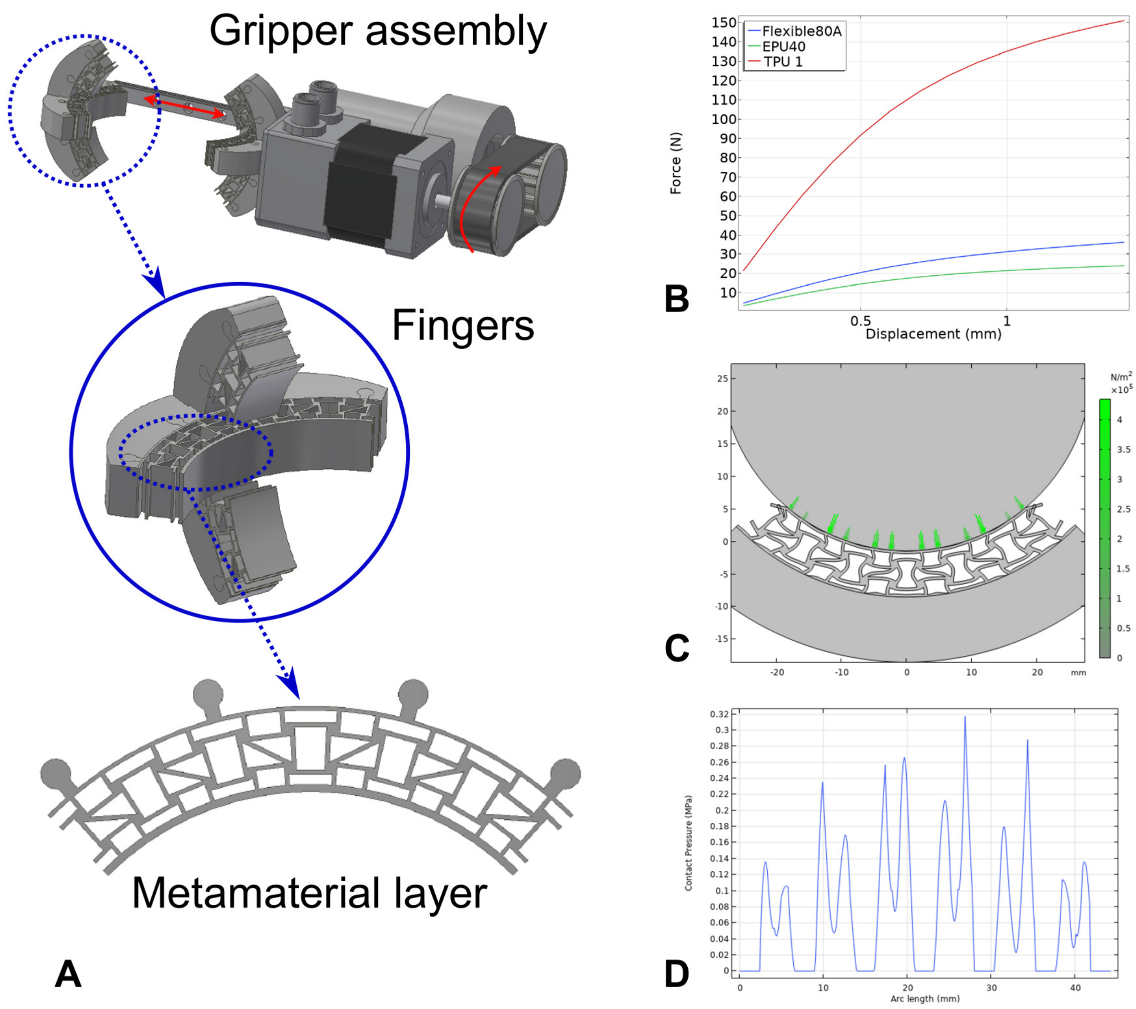

Fig. 1: a) Design of a gripper with the main components of the gripper assembly, gripper pad, and the optimized achiral metamaterial layer. b) Simulated force-displacement curves for the three analyzed constituent materials. c-d) Contact pressure (in green) for the optimized metamaterial design.

We also simulated the conditions of imperfect alignment and poor contact due to shape irregularities, which also revealed a very good grasping performance of the metamaterial gripper.

III. Experimental testing

To validate the predicted results, we performed three sets of compression tests (Fig. 2). In the first set, we compressed 40 tomatoes with rigid cylinders to identify rupture conditions (Fig. 2, right). We distinguished local piercing, sepal burst, and severe local deformations that occurred below 50 N load due to the localized load area under the rigid cylinders. The other two test sets served to validate the predicted grasping performance of the metamaterial grippers in comparison with their comparatively rigid (FDM TPU) counterparts of the same contact area. The tomatoes experienced up to 12 mm displacements in cyclic loading gradually increasing with a 5 N step. The tests proved the advantage of the metamaterial grippers that preserved the integrity of all 40 tested tomatoes, while the TPU grippers damaged most of tomatoes. We attribute the good performance to the combined effect of a large contact area, shape adaptability, and optimized rigid-soft behavior with uniform contact pressure distribution.

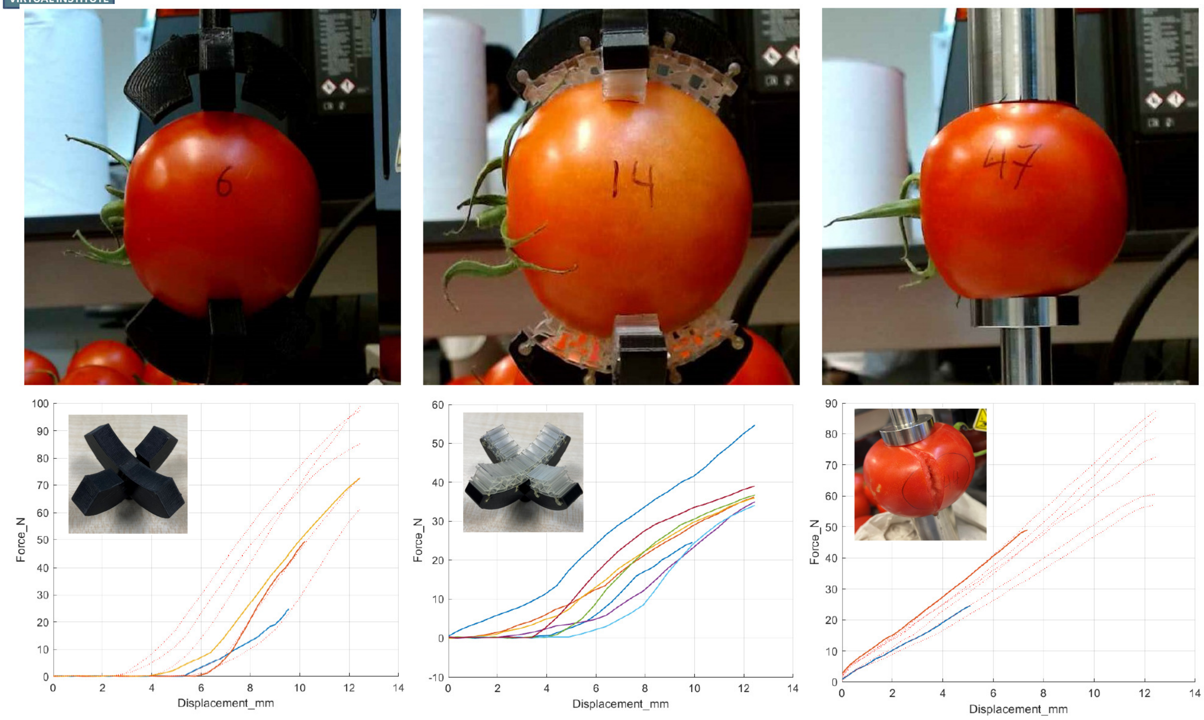

Fig. 2: a) Compression tests with solid TPU and metamaterial SLA Flexible 80A grippers and rigid cylinders on classic truss tomatoes. The dashed lines correspond to the cases of damaged tomatoes.

IV. Conclusion

We developed the design of a metamaterial gripper with two extended fingers and the optimized achiral metamaterial interface for improved shape-morphing and uniform contact pressure. The experimental tests of SLA 3D-printed prototypes validate the predicted grasping by preserving the integrity and quality of classic tomatoes in a sensorless actuation. In our future work, we aim to analyze the plucking process and reduce the gripper's dimensions to extend their potential to practical utility. We believe that this research will further stimulate highly demanded automation in the agri-food industry of fragile crops.

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