Printable Soft Grippers with Integrated Bend Sensing for Handling of Crops

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Soft pneumatic grippers are made from flexible materials that deform upon pressurization to generate a passively compliant bending motion analogous to grasping [1]. The soft fingers can adapt to objects of varying shapes and delicacy as their morphology interacts with the target object. The inherently safe and adaptable nature of this class of grippers encourages its use in applications that require gentle interaction with delicate targets of variable geometries, such as biological sampling [2] and minimally invasive surgeries [3]. An interesting application for the agri-food sector, is the safe handling of delicate crops without causing any damage or bruising.

Commonly soft pneumatic grippers are made of stretchable silicone rubbers that are shaped using 3D printed molds to create the required morphology following a multi-stage lamination and curing process [4]. This fabrication process is simple and inexpensive to implement, yet it is limited in terms of its accuracy and repeatability due to its manual multi-stage nature. Thus, more automated fabrication approaches are desired for a faster, more accurate and consistent output of various soft robotic components [5]. Another key challenge related to soft grippers, is the limited feedback and control over their grasping behavior [6]. A sensor-guided soft gripper would be more reliable as it can detect contact with the target object and automatically adjust the pneumatic supply accordingly. This way excessive bending that could damage delicate targets or result in unstable grasps can be avoided.

In this work we present a customizable soft gripper with integrated bend sensing capability, which can be entirely 3D printed using common FDM printers and commercially available material filaments. The softness of the gripper fingers enables fruits and vegetables to be grasped gently, while the integrated bend sensors are calibrated to provide bending feedback and contact detection. This way excessive pressurization that could bruise the crops can be avoided, as the supplied pneumatic pressure is adjusted based on the continuous sensory feedback. Therefore, the proposed soft gripper not only benefits from the passive compliance of its soft body, but also utilizes additional sensing capability for a more controllable and reliable performance.
A standard FDM printer was used to directly print a two-fingered soft gripper, following the pleated morphology, from a flexible material filament (NinjaFlex). By tuning the print parameters, a highly flexible air-tight soft gripper was successfully printed (**Fig. 1**) with a shell thickness of only 0.6 mm and sidewall thickness of 0.9 mm . Furthermore, using a dual-extrusion FDM process, flexible resistive strain sensors were

also successfully printed from the same flexible material, while simultaneously printing the conductive tracks from conductive PLA filament (**Fig. 1**). Bending the sensor causes a change in the overall resistance of the conductive tracks, which can be amplified and converted to a voltage output. The sensors response exhibits some drift due to heating that becomes more evident for longer actuation durations, as it is the case with resistive sensors. The advantage of printing the sensor lies in the ability to customize low-cost sensors flexible sensors based on the desired dimensions of the soft gripper fingers, rather than being limited to the commercially available flex sensors. Also, the printed sensor can be easily welded to the base of the gripper fingers, since they are both made from the same flexible material. This results in a printable soft gripper that can be integrated with bend sensing capability and customized according to the application needs.

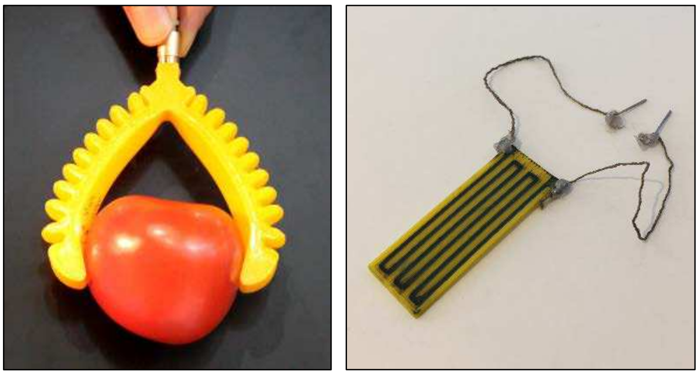

Fig. 1. (a) A directly printed two-fingered soft gripper gently grasping a tomato. (b) A printed flexible strain sensor sample showing the conductive tracks (black) and flexible body (yellow).

An experimental setup involving a pneumatic control board and a calibrated high-speed camera was used to systematically test individual printed soft finger samples with the integrated strain sensors, in order to calibrate the sensor's feedback against real bending angle values. It was shown that using basic regression algorithms, simple empirical models can be derived to accurately describe the free-bending response of individual printed actuators based on the combined sensory feedback from the integrated strain sensors and onboard pressure sensors [7]. Thus, contact with the grasped object can be detected by simply monitoring the difference between the measured bending response and the previously modelled free-bending response at the same input pressure. Furthermore, current investigations have shown that the distance between the two opposing soft gripper fingers can be described using simple empirical model, based on the combined sensory feedback from those two fingers and the measured internal pressure. Hence, the bending of individual soft fingers be measured during grasping to detect when contact occurs, while the grasped object size can be estimated based on the combined feedback from both gripper fingers. Therefore, the addition of such sensing capability to printable soft grippers would enable a more controlled grasping process that benefits from the softness of the fingers to passively conform to grasped crops, while utilizing the sensory feedback to maintain a gentle and stable grasp.

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