Fully Printable Low-Cost Dexterous Soft Robotic Manipulators for Agriculture

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Abstract

Further automation of agricultural tasks will require the development of new dexterous end-effectors that are capable of directly interacting with soil and vegetation alongside human workers. Soft robotic end-effectors are poised to provide feasible low-cost solutions, but their design and fabrication process is still time-consuming, difficult, and not well established. In this work, we present an approach that utilizes novel low-cost fabrication techniques in conjunction with design tools helping soft hand designers to systematically take advantage of multi-material 3D printing to create dexterous soft robotic end-effectors. While very low-cost and lightweight, we show that generated designs are highly durable, surprisingly strong, and capable of dexterous grasping, making the technology an ideal candidate for real-world agricultural applications.

Introduction

Agriculture is required to grow significantly in terms of productivity, sustainability and resilience to keep up with the rising global food demand (Duckett et al. 2018). Artificial intelligence (AI) and robotic technologies promise to bring about a technological transformation that will help to further automate food production by assisting human workers carrying out repetitive and strenuous tasks. While many of the current robotic applications in agriculture focus on gathering information using computer vision technology (Singh et al. 2016; Patrício and Rieder 2018; Chlingaryan, Sukkarieh, and Whelan 2018), further automation will inevitably require the development of robotic technologies that can safely interact with soil and vegetation alongside human workers. However, many of the manual tasks observed in harvesting or pruning require specialized dexterous manipulation capabilities, such as moving branches or foliage to access hidden objects to make cuts (Yandun, Silwal, and Kantor 2020). Such tasks largely remain out of reach for current robotic manipulators. Similarly, the development of highly customized manipulators and end-effectors for harvesting high-value crops such as apples, kiwifruit and tomatoes (Hua et al. 2019) or for manipulating sorghum (Parhar et al. 2018) has not yet resulted in widespread adoption of robotic solutions in the field. This can be attributed to the core challenge of consolidating design, control and sensing of robotic end-effectors with the harsh real-world operating conditions and demands for low-cost operation, and maintenance.

Traditionally, dexterous robot end-effectors require a large number of parts and actuators to realize complicated joint mechanics (Shadowhand 2004; Xu and Todorov 2016; Biomimetic 2020). Aside from the tedious assembly, changes to form and function of individual parts are often costly, time consuming, and difficult to achieve without a complete redesign and testing of the end-effector. Furthermore, rigid robots require complex control and sensing strategies to overcome their lack of compliance and operate safely in the field.

Figure 1: Soft hand design fully printed from flexible TPU-filament performing a variety of dexterous grasps on objects of different shapes.

In contrast, soft robotic end-effectors are uniquely suited to gently handle soft fruit and vegetables. In addition to the benefits associated with simpler control through underactuation and compliance, soft robots also promise lower costs for maintenance and assembly. This is achieved by greatly reducing the number of parts needed in an end-effector by replacing intricate rigid body joint mechanics with simple compliant mechanisms (Odhner et al. 2014). However, a common disadvantage of soft robots is that manufacturing usually requires a time-consuming multi-step fabrication process that involves mold making, casting, curing and support removal (King et al. 2018; Pneuflex 2020). Additionally, soft end-effectors are inherently difficult to model, often requiring the support of specialized finite-element-method (FEM) simulation to account for complicated soft body contact dynamics and continuous deformation behavior resulting from soft materials (Elsayed et al. 2014; Schlagenhauf et al. 2018; Tawk et al. 2019). As a result, determining end-effector morphology and placement of actuators remains challenging and requires technical expertise, intuition and multiple iterations of designing, fabricating and testing design candidates (Teeple et al. 2021).

To address these shortcomings, we make the following contributions. Firstly, we introduce a novel rapid prototyping process for tendon-actuated soft end-effectors through the coupling of fast kinematic grasp simulation and design modification, effectively enabling a systematic, data-driven approach for testing the behavior of soft manipulators in relation to design changes *prior* to fabrication. Secondly, we propose a low-cost fabrication process for fully printable tendon-driven soft robots of variable stiffness using only low-cost fused deposition modeling (FDM) printers, commercially available flexible filaments, and off-the-shelf materials (fig. 1). With upfront costs for tools and printers of less than \$1000, minimal assembly, and no post-processing requirements, we believe this process can make soft dexterous end-effectors accessible to the field of agriculture.

Printable Soft End-Effectors for Agriculture

Design Requirements and Constraints

Agricultural manipulation poses a set of unique challenges to robotic end-effector design. In contrast to handling a set of known parts in a controlled environment, fruits and vegetables can vary significantly in terms of shape, size, and weight. Consequently, end-effectors need to be able to handle large object variations and apply sufficient force while still being soft and compliant.

Aside from these task-related requirements, end-effector designs are subject to several economic constraints that demand low initial and operational costs. While initial costs are easily quantifiable, achieving consistently low operational costs requires a much broader consideration of the design with respect to operating speed, reliability, maintenance costs and adaptability to other tasks.

Finally, to achieve widespread adoption of dexterous robotic end-effectors the technology has to be able to withstand real world conditions including cold and hot temperatures, high humidity, mud or rain.

We hypothesize that for traditional rigid robotic end-effectors it is unattainable to satisfy all of the above mentioned requirements and constraints. Soft end-effectors on the contrary, can intrinsically provide the required compliance for handling delicate fruit and vegetables without bruising, or moving branches and foliage without damaging it. Furthermore, recent advances in FDM-printing technology, specifically desktop 3D-printing, have made additive manufacturing technology more accessible to the broader public, while significantly lowering fabrication costs and lead times for iterative prototyping. The use of this technology in combination with low-cost flexible filaments can thus enable the production of very low-cost soft manipulators without the need for expensive manufacturing equipment or dedicated machine shops. Combined with the ability to print entire end-effectors in one part, additive manufacturing promises to greatly reduce cost, assembly, and maintenance efforts, and allows to create a variety of customized end-effectors, which can be tailored to different tasks.

Iterative Design Framework

To aid and accelerate the design process of soft robot end-effectors for rapid prototyping, we present a framework to generate, iterate and evaluate end-effector designs for tasks recorded from human demonstration. This framework, outlined in fig. 2, builds on our previous work, which introduced a method to directly transfer grasps and manipulations performed by human subjects between objects and hands by utilizing contact areas (Lakshmipathy et al. 2021).

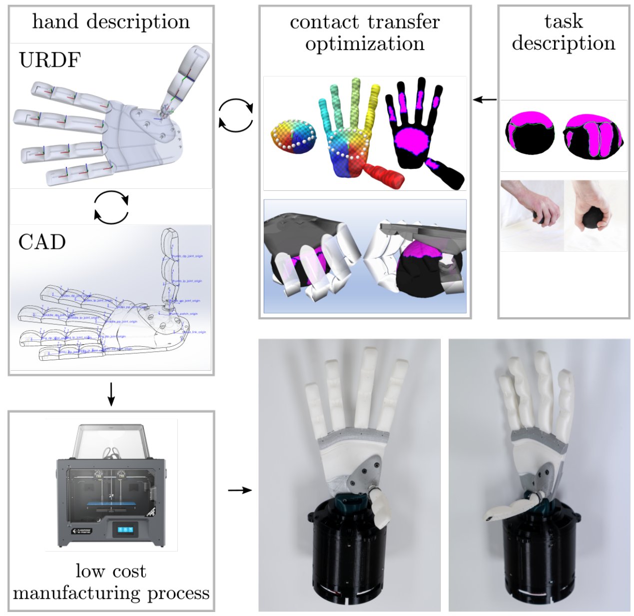

Figure 2: Framework integrating simulation testing into the design and fabrication process of soft end-effectors. Starting from a design candidate in URDF-format we evaluate designs using our contact transfer optimization approach (Lakshmipathy et al. 2021).

We encode the high-level information of a soft end-effector design using the Unified Robot Description Format (URDF), which represents a joint-based description and is widely used for rigid robot hands and grippers. While this format is generally not capable of describing continuous deformations of soft materials, we show that by incorporating joints using design features such as bumps, creases, and material combinations, we can approximate kinematic behavior of soft end-effectors using quasi-rigid approximations. This allows us to quickly evaluate end-effector capabilities in simulation.

Our processing pipeline is depicted in fig. 2 for an anthropomorphic hand. Starting with an initial URDF model we import joint origins and axes into our computer-aided-design (CAD) software (SolidWorks, 2021). We utilize geometric features and material combinations to create flexible joints that we place along the kinematic chain to create a CAD-model of the hand. Then, we export meshes of individual links and incorporate them into the URDF model, which is done in one step using the SolidWorks URDF add-on.

To evaluate the generated hand design with respect to a certain task, we use our contact transfer process (Lakshmipathy et al. 2021) to quickly synthesize kinematically feasible whole hand grasps. We account for underactuation resulting from tendon routing by modeling the relation between dependent and independent joints as linear equality constraints. Using our contact transfer optimization process we can quickly visualize feasible hand poses and grasps and use this visual feedback to make informed design decisions e.g. in terms of joint type and placement, or link lengths. Since the central representation of our approach is encoded in the URDF format, making changes to the design is straightforward.

Overall, this framework allows us to quickly iterate through generating a variety of end-effector designs and evaluating their performance. An example is given in fig. 3: The top row visualizes hand poses to grasp a bowl, box, lemon, and wineglass found by our contact transfer optimization process; the bottom row shows the corresponding grasps achieved using the fabricated end-effector.

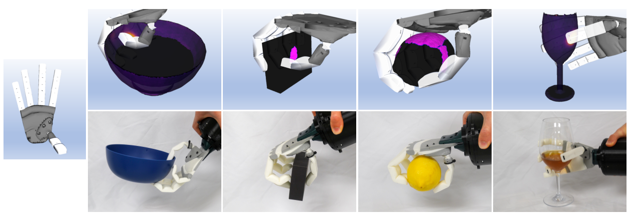

Figure 3: *Left*: Soft hand design. *Top row*: Synthesized grasps found by contact transfer optimization process. *Bottom row*: Corresponding grasps using the real soft hand.

Fabrication Process

We propose a low-cost fabrication process using desktop 3D printers and off-the-shelf materials. All mechanical parts are printed using a FDM-printer with independent dual extrusion from Flashforge (Flashforge Creator Pro 2). In order to print flexible materials of varying shore hardness (75A–95A) we retrofit the printer with extruders from Flexion[1].

We use NinjaTek Chinchilla[2] (Shore Hardness 75A) and Cheetah[3] (Shore Hardness 95A) filaments to print the soft end-effector parts, both of which are commercially available thermoplastic polyurethane (TPU) filaments. Rigid wrist parts are printed from standard PETG filament.

The soft hand shown in fig. 2 is actuated by seven tendons; each finger in the hand featuring one flexor tendon, with the thumb featuring two additional tendons for adduction/abduction. Tendons are routed through ⌀1 mm wide channels that are printed directly inside the hand and are made from standard monofilament fishing line with a diameter of $0.61mm$ and a rated tear strengh of $178N$. To secure the tendon we print small dumbbell shaped anchors from PETG material and tie the tendon around the anchor using an improved clinch knot.

Each tendon is driven by a brushless DC (BLDC) electric motor. The motors are contained in a compact lightweight wrist design (total weight: $648g$, soft hand excl. wrist: $94g$), which can be mounted on robot arms (as shown in fig. 1 *center and right*). The assembled hand design is fully self-contained requiring only a USB-cable for serial communication and a 24V DC power supply. Depending on the size of the end-effector, a full print can take between $5 - 18$ hours due to the relatively slow printing speeds of flexible filaments. Once finished printing, assembling the end-effector is a matter of attaching the soft components to the wrist, inserting the tendons through the channels and securing them by tying a simple knot. This all can be done in under one hour.

Each soft end-effector can be fabricated independently of the wrist for less than $\$5$ in costs for TPU filament. The wrist design costs $< \$800$ in parts with servo motors ($94/motor) making up for the bulk of the cost. The total upfront costs for the desktop 3D printer ($\$599$), custom extruders ($\$249$), and tools (soldering iron, pliers, screwdrivers etc.) are $< \$1000$, making this fabrication process less expensive than popular smartphones at the time of writing.

Application to Agriculture Tasks

We hypothesize that it would be possible to obtain contact information from human demonstrations for harvesting fruits and vegetables using our existing approach. This could either be done by painting crops with thermochromic paint or by exposing thermal signatures using thermal imaging. Unfortunately, capturing interactions with foliage and branches would be significantly more difficult and likely not feasible with our current approach. However, incorporating and testing new end-effectors in rigid body simulators in combination with existing robot arms would be trivial given that our designs can be represented in standard URDF format. This means that design candidates could not only be seamlessly integrated with existing plant simulations (Yandun, Silwal, and Kantor 2020), but also tested and validated against synthetically generated grasps or manipulations.

Our soft end-effectors can achieve stable grasps without the use of tactile sensing, and given their intrinsic compliance, are able to handle delicate objects without damaging them. We demonstrate the durability and robustness of these grippers in the experiments section below. Since our fabrication process allows to quickly create variously shaped and sized end-effectors, designs can be easily tailored to agricultural tasks. The current wrist design only requires a USB connection and a 24V power supply, making it straightforward to integrate into existing manipulators.

Since grippers and even more complex end-effector designs can be fully printed in one part, assembly and commissioning the robots does not require expert knowledge. Maintenance is equally straightforward as damaged grippers can be replaced as a whole and recycled subsequently.

We believe flexible TPU filaments are well suited for real-world agricultural applications due to their high abrasion and tear resistance and their ability to withstand a large range of temperatures. Additionally, printed TPU end-effectors are resistant to hydrolysis and various other chemicals[4] that

[1] https://flexionextruder.com/shop/dual/

[2] https://ninjatek.com/shop/chinchilla/

[3] https://ninjatek.com/shop/cheetah/

[4] https://ninjatek.com/wp-content/uploads/Chinchilla_CR.pdf

could be used to clean and disinfect them regularly. Finally, TPU materials are considered safe for food contact.

Experiments

Durability To demonstrate the durability and strength of the printed soft end-effectors, we clamp one individual soft finger printed from Ninjatek Chinchilla and actuate the finger repeatedly until exhaustion using a servo motor. The finger weighs $10g$ and features three creases. We keep the tendon contraction length constant and observe material behavior by tracking colored markers on the joints using a RGB-D camera. The resulting finger motion is shown in fig. 4 *a*. The first 50 iterations are considered a *break-in* period, during which any leftover debris inside the tendon channels is cleared and smoothed out by the tendon movement, and our evaluation begins after this period. We plot the fingertip position in the extended and the fully flexed configuration over experiment iterations (fig. 4 *b*–*d*) and show overlayed images of iteration 1 and 4000. Fingertip positions are marked in color corresponding to iteration. Hysteresis of the fully extended finger configuration is depicted in fig. 4 *b*. In the fully flexed configuration (fig. 4 *c, d*) fingertip positions are largely consistent over time, with a maximum distance of $2.99mm$ between positions throughout the experiment. No visible damage to the material is found after 4000 flexion and extension motions.

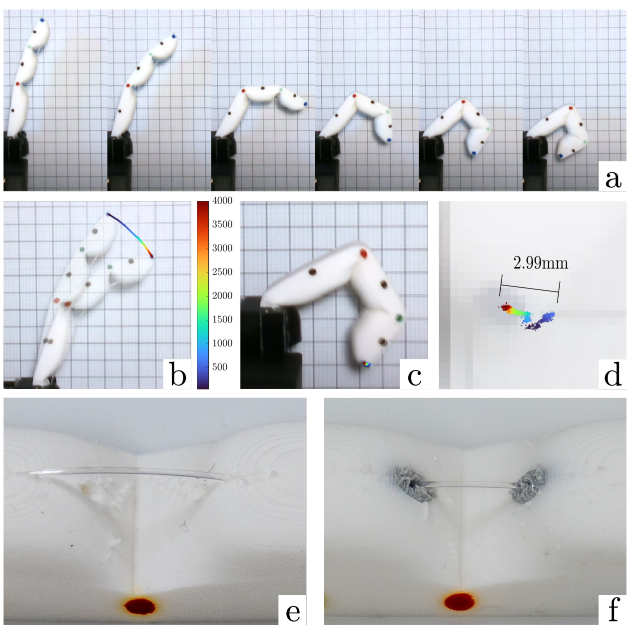

Figure 4: Durability experiment setup (*a*). Fingertip position in extended (*b*) and fully flexed (*c*) configuration over time. Overlayed images of iteration 1 and 4000 are shown, fingertip position is marked in color corresponding to iteration. Close-up of fingertip position in flexed configuration over time (*d*). Damage to the printed tendon channels caused by 5200 cycles of excessive tendon actuation (*e*). Printed rigid material inserts reinforce the tendon channels (*f*). No damage is visible after 5000 cycles.

To stress test the material's ability to withstand excessive strain, we conduct a second experiment where a finger is repeatedly actuated beyond its fully flexed configuration (fig. 4 *a, far right*) until exhaustion. Over time we observe that the tendon slowly cuts through the fingertip patch material as shown in fig. 4 *e*, causing small changes in finger motion and final flexed configuration. This increases friction between tendon and finger patch, resulting in hysteresis.

Based on these results, we test a finger where tendon channels are coated with a thin layer of harder material (NinjaTek Cheetah) under the same conditions and find that the revised design shows no signs of cutting or material fatigue after 5000 iterations as depicted in fig. 4 *f*.

Strength To evaluate the strength of individual fingers, a pull-out force test is carried out as shown in fig. 5. A hook attachment is grasped by a flexed finger, and the force required to cause pull-out is measured using a force gauge. The finger withstands a maximum load of 37.4N before slipping, and no visible damage to the finger is observed.

Figure 5: Individual finger strength test: In the flexed configuration, the finger withstands a maximum load of 37.4N.

Conclusion

Automating repetitive tasks such as harvesting or pruning will require the development of new intelligent end-effectors that are dexterous, low-cost, and robust. We presented an approach that utilizes novel low-cost fabrication techniques in conjunction with design tools helping soft robot designers to systematically take advantage of multi-material 3D printing. Our approach tightly integrates simulation testing with the fabrication process, allowing designers to better understand how design changes or the introduction of new design features will influence the end-effectors kinematic capabilities. We also showed that our low-cost fabrication process yields durable, robust designs that require little assembly and can perform a variety of dexterous grasps.

Due to its simplicity, this technology could not only be deployed on a large scale in the form of highly specialized designs but would also be accessible to small farms that may only need a few end-effectors with varying capabilites.

Acknowledgments

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