Soft Robotic Gripper With Compliant Cell Stacks for Industrial Part Handling

Metodi Netzev, Alexandre Angleraud, and Roel Pieters

Abstract—**Robot object grasping and handling requires accurate grasp pose estimation and gripper/end-effector design, tailored to individual objects. When object shape is unknown, cannot be estimated, or is highly complex, parallel grippers can provide insufficient grip. Compliant grippers can circumvent these issues through the use of soft or flexible materials that adapt to the shape of the object. This letter proposes a 3D printable soft gripper design for handling complex shapes. The compliant properties of the gripper enable contour conformation, yet offer tunable mechanical properties (i.e., directional stiffness). Objects that have complex shape, such as non-constant curvature, convex and/or concave shape can be grasped blind (i.e., without grasp pose estimation). The motivation behind the gripper design is handling of industrial parts, such as jet and Diesel engine components. (Dis)assembly, cleaning and inspection of such engines is a complex, manual task that can benefit from (semi-)automated robotic handling. The complex shape of each component, however, limits where and how it can be grasped. The proposed soft gripper design is tunable by compliant cell stacks that deform to the shape of the handled object. Individual compliant cells and cell stacks are characterized and a detailed experimental analysis of more than 600 grasps with seven different industrial parts evaluates the approach.**

Index Terms—**Soft robotics, grasping, grippers and other end-effectors.**

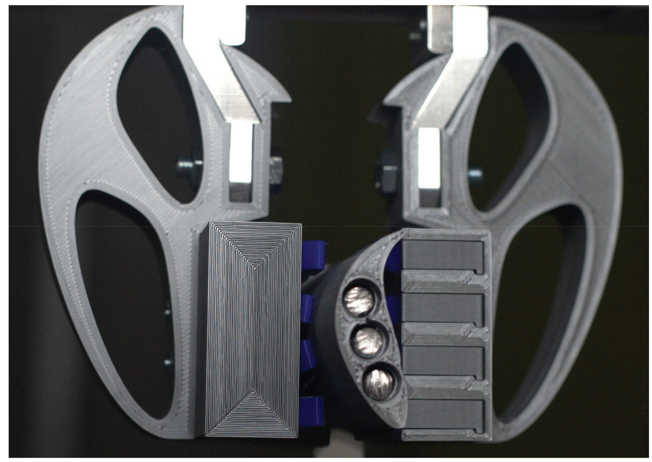

Fig. 1. Soft gripper design (grey) with compliant structures (blue) successfully holding a mock turbojet turbine blade (grey curved object with three weight inserts). The compliant structures deform to the shape of the object, which would not be possible with a rigid parallel gripper.

I. Introduction

ROBOTIC object grasping and manipulation are commonplace in industrial manufacturing. For high-throughput assembly lines, fast and accurate grasping is typically established by custom-made bulk feeders [1] and standard parallel gripper mechanisms [2]. However, these solutions are unsuitable in custom manufacturing, which requires flexibility and reconfigurability following task changes. Ongoing research efforts towards (bin) picking disregard feeders and utilize sensing to detect objects and their grasp pose for handling [3], for example by deep convolutional neural networks (CNNs) trained on large datasets of grasp attempts in a simulator or on a physical robot [4], [5]. Such approaches assume the gripper design suits the object and its grasping pose, which, in case of complex object shape or deformable objects, is not necessarily true. One example are (jet engine) turbine blades that typically have a large variety in surface geometry (see Fig. 1). The blade profile contains a complex, Bézier curve described profile with convex and concave sides. Gripping such blade with a straight and rigid parallel gripper creates two small contact patches on the concave side and one small contact patch on the convex side, which might not be sufficient for a stable grasp. In addition, increasing the grasp force to prevent slippage is unsuitable in case of delicate and fragile objects.

Soft grippers are one solution that enable the handling of complex-shaped and fragile objects (see Fig. 1). An engineered soft gripping surface introduces controllable flexibility to object handling and has the following benefits:

- A gripper conforming to the profile of an object creates a larger combined contact surface. The applied force is distributed evenly, reducing the point pressures and the possible damage that could result from slip. This also increases the possibility to envelop the object.
- The material properties of a soft gripper determine its stiffness and therefore its capability to adapt to the shape of the object.
- A soft gripper can handle objects with completely inverse contour (no gripper changeover necessary) and does not

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The authors are with the Cognitive Robotics group, unit of Automation Technology and Mechanical Engineering, Tampere University, 33100 Tampere, Finland (e-mail: metodi.netzev@tuni.fi; alexandre.angleraud@tuni.fi; roel.pieters@tuni.fi).

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require an accurate grasp pose, as long as the object fits the gripper.

Proposed in this work is a soft gripper design, motivated by the handling of small and light (<1.0 kg) objects with complex shape. Its design is aimed to fulfill the need for a soft gripper without the complexity of changing the gripper for different parts. Following, an overview of related work is given.

A. Related Work

The rise in interest towards soft and flexible robots [6], [7], has been made possible by a combination of technologies. Most notably, the increased reliability of additive manufacturing technologies has enabled 3D printing to become a norm in rapid prototyping through Fused Deposition Modelling (FDM), Computer-Aided Design (CAD) and an abundance of materials that can be adjusted to meet flexibility requirements. Gripper design for soft and flexible end-effectors have benefited from this [8], by various shapes and configurations (e.g., discrete and flexible links, serpentine robots and continuum manipulators). A promising concept in the actuation and motion of soft robotics gripper technology is flexible hinges as opposed to geared or machined joints. This technology has the potential for no backlash, higher accuracy movement at a smaller scale and lower price. This is further enabled by the ability to handle large forces due to inadvertent contact [9]. Another benefit is that irregular (e.g., food [10]), or thin and flexible objects [11] can be grasped without knowing their shape beforehand [12]. In similar nature, gripper design has taken inspiration from self folding origami structures [13] or Gecko-like adhesive [14].

Demonstration of flexible structures adapting to the shape of an object, is shown in [15]. Another form of compliancy is shown in [16], demonstrating a material design for robots to overcome environmental challenges by deforming and conforming their bodies (i.e., for movement through confined spaces). Related work by Kaur *et al.* [17] demonstrates a compliant three-fingered gripper for grasping objects. The gripper is equipped with 3D-designed cellular fingers and can exert a gripping force of 16 N. Finally, research by Chin *et al.* has proposed compliant electric actuators based on Handed Shearing Auxetics for a two-fingered gripper, and shows the gripping of several house-hold objects [18]. Continuation of the work included high-deformation haptic feedback to enable object classification [19].

B. Application

The significance of the proposed gripper design is motivated by two industrial (dis)assembly processes. Manufacturing, servicing and maintenance of jet and Diesel engines implies the disassembly of the complete engine, ultrasonic cleaning of individual parts, surface inspection with non-destructive testing methods (e.g., liquid penetrant testing) and final reassembly [20]. The process requires handling of individual parts and small sub-assemblies. Turbine blades and pistons attached to conrods have organic and complex shapes with varying sizes and weights. For example, the Orenda 10 Turbojet engine contains 91 vaned, ceramic coated blades in the hot end section with 12 stages and more than 800 blades to remove in total [21]. This is further complicated by engine parts being precision engineered to reduce rotational mass and increase cooling, requiring delicate handling without the presence of ergonomic grips. Servicing is time-consuming and done manually, requiring certified and skilled operators. Robotic assistance can support these operations through collaborative or semi-automated handling of individual parts. A first step towards such support is by the proposed gripper design that is capable of grasping and lifting components.

C. Contributions

The gripper design proposed in this work (i.e., compliant cell stacks and gripper adapter) falls in the two-fingered linear end-effector category, however, it should be considered as two soft surfaces. Grasping occurs when the gripper pads are linearly translated by the end-effector to make contact with the part (see Fig. 1). Where a traditional gripper would grasp the object on the outside, the cell stacks have the capability to envelop an object within the cell array size and maximum vertical cell deflection.

The contributions of this work are as follows:

- Design of a soft robotic gripper with 3D compliant cell stacks and cell stack array.
- Compliant cell and cell stack characterization.
- Experimental grasp comparison of the proposed soft gripper to two traditional grippers with over 280 grasps.
- Experimental analysis of the proposed soft gripper design with seven industrial objects (i.e., turbine blade mock-up, different Diesel engine parts and tools) and over 600 grasps.

The organization of this letter is as follows. Section I introduces the work by motivating the need for soft robot grippers. Section II describes the soft gripper design with its required properties. Section III presents the results of the design by characterization of the compliant cell stacks and a thorough experimental analysis utilizing two other grippers and seven industrial parts and tools. Section IV and V discuss and conclude the work.

II. Materials and Methods

A soft gripper design should allow compliance and lateral force distribution during grasping through shape conformation to the object. Unequal loading during compression is therefore decreased with the effect of mechanical retention; holding instead of grasping (prehension). Compliant mechanisms enable such properties [22]. Following, this section presents the compliant cell stack and array design, based on the technical requirements as specified in Table I.

A. Cell Compliance

Compliant cells are manufactured in their uncompressed form and should deflect to a predefined closure distance. This can be controlled through stiff pillars and flexible hinges (side springs) in each cell (see Fig. 2) and are adjusted based on the required cell and gripper properties, which, in turn, are dependent on the use case. A detailed taxonomy of kind, category and family of joint sections is described in [22] and [23]. Vertical movement is

TABLE I
GRIPPER TECHNICAL REQUIREMENTS

Feature	Value
Turbine blade profile height	16.6 mm
Maximum profile difference for parts/tools	15 mm
Gripping force	100 N
Maximum gripper deflection[1]	10 mm
Minimum gripper length[2]	39.9 mm
Maximum payload	1.0 kg
Maximum gripper weight[3]	1.0 kg
Minimum printable detail thickness[4]	0.8 mm

1-Allowed object width tolerance due to industrial robot gripper.
2-Specifies resolution of array.
3-Including robot parallel gripper (0.7 kg).
4-Default limitation of slicer software.

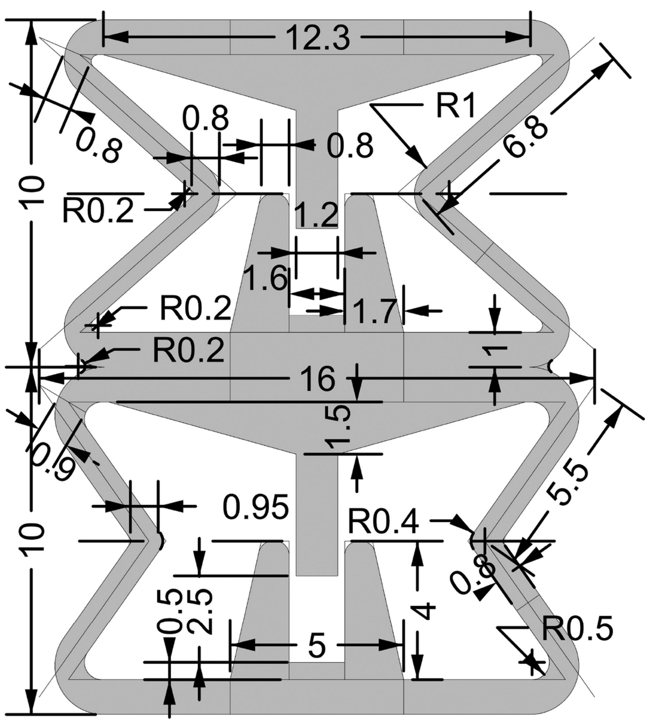


Fig. 2. Design of the compliant cell stack (dimensions in [mm]). Top cell has longer springs and requires 4.5 N for 2.5 mm compression, while the bottom cell, with shorter springs, requires 12.5 N for 2.5 mm compression. Depth of the cell stack and 3D printing height is 6 mm.

constrained by the stiff, central pillar coming into contact with the bottom support structure when compressed. The high axial stiffness of the pillar maintains flexure of the springs at a safe limit as increasing vertical force is applied. Thus, regardless of the grasping force, the springs can recover their original shape.

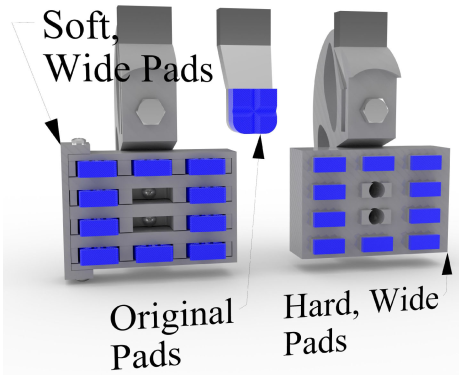
Motion ratio-based control of structural compliance allows for the variation in structural stiffness while maintaining a desired joint stiffness, thickness or stress. The phenomenon is commonly observed on race cars with push or pull rod suspension systems. It can be seen as allowing large motion ratios at the wheels for small spring travel distances in the suspension, or in the compliant cell case as a reduction in stiffness during downwards travel. The aim of the cell stack is allowing the cells in the top rows to compress before the cells at the bottom of the structure, doing so in a controlled manner and with a desired force (see Fig. 2). The proposed hour glass design has the highest possible horizontal inwards stretch as a result of vertical compression. Since large movements mean large motion ratios it provides a low spring stiffness. It is also the easiest to constrain in terms of movement. The dimensions of both top and bottom cell types in the stack, i.e., $16 \times 10 \times 6$ mm (W×H×D), is found through a trade-off between stiffness, deflection and smallest 3D printing size (see Fig. 2). In particular, the minimum printing detail thickness (0.8 mm) determines the outer dimensions of a smallest possible cell stack, while the maximum gripper deflection (10 mm) specifies the allowed deflection per cell stack (5 mm per gripper side). Considering a maximum gripping force (100 N) to be distributed over an array of cell stacks, a cell stack was designed with a top cell that requires 4.5 N for full closure and a bottom cell that requires 12.5 N for full closure. This implies half-closure of a cell stack was designed to require 4.5 N.

B. Cell Material

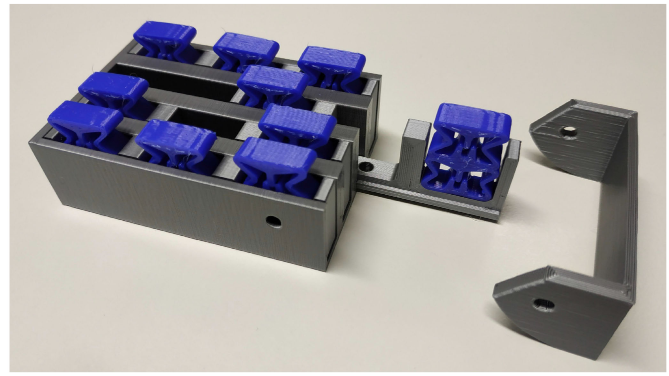
The material of the flexible hinges (side springs) should have a low Young's modulus and a low stiffness, to allow for an array of cells distributed over the gripper. Vertical deflection of a cell is constrained by the maximum force supplied by the gripper and desired life duration. Therefore, maintaining a high vertical column travel of the compliant cell stacks is achieved and controlled through the thinnest manufacturable hinges and straight elements. These characteristics can be met through use of silicone or TPC (thermoplastic copolyester) like materials. The more flexible they are, the more they can be discretised, producing larger displacements. The result is smaller, mechanically controllable gripper pad cells. Bulk materials can handle more shear stress than the mechanical cells but are heavier and stiffer for a given displacement. If porosity is introduced into the bulk material, the amount of displacement for a given force will be increased alongside a reduction in weight until the cell springs are extended past their elastic memory limit. For grip, a large contact surface produces the lateral or longitudinal forces, lifting the work piece under a given normal force applied to it. The more force applied, the higher the concern of damaging the object or gripper if there is slippage. This provides a motivation to increase the total contact patch. Because this is done through an increase in parallel, compliant cell count (see Fig. 3(a)), the equivalent spring constant is added for each cell.

C. Cell Array Design

The compliant cell stacks require even distribution over the gripper such that most contact points are made with a gripped object. A gripper with 20 cell stacks (see Fig. 3(b)), theoretically requires 90 N (20×4.5 N) for half closure (i.e., only top cell closed) and 250 N (20×12.5 N) for full closure. In case not all cells are in contact with an object, the maximum gripping force available (100 N) will only fully compress the gripping surface with less than 8 cells engaged. The dimensions of the gripping area is determined by the objects to grasp and designed with $5 \times$



(a) The different grippers used in this work depict the differences in contact surface area of the gripper pads (blue).



(b) The proposed gripper with compliant cell stacks (TPC) fitted to the attachment rail, which slides into the cassette design (both PLA).

Fig. 3. Different gripper models used for design and comparison.

$10 = 50\,\text{cm}^2$ footprint and a possible $10 \times 1.6 \times 0.6 = 9.6\,\text{cm}^2$ contact area.

D. Testing Methodology

The methodology for testing our proposed soft gripper includes the characterization and benchmarking of the gripper and the testing of grasping. Individual compliant cells are compressed to their closure distance and the corresponding closure force is compared to the designed closure force. Benchmarking of the proposed soft gripper is done by comparison to two other grippers; a robot provided gripper and a hard version of the proposed design (see Fig. 3(a)). Grasping is assessed in terms of distance within which it is possible to successfully grasp several industrial objects. Success of the grasps is depicted in three (colored) categories: successful grasp, lift and put-down (green), successful grasp and lift, but not put-down, as e.g., the object moved in the gripper (yellow), and failed grasp (red). Grasp locations over the object are segmented into vertical and horizontal steps (10 mm), with the origin located at the lower outer corner of the gripper (see Fig. 3(a)).

III. Results

The soft gripper design is evaluated by the characterization of individual stacked cells, benchmarking of the soft gripper by comparison to the original gripper pads and a solid version, as well as by numerous (>600) grasps with seven different industrial parts and tools.

A. Cell Fabrication

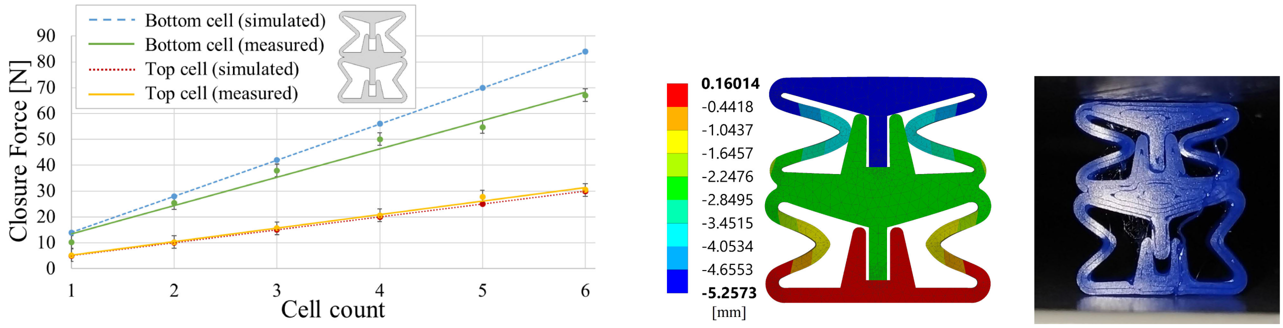
Cell stacks are fabricated from TPC with a Prusa i3MK3 Fused Deposition Modelling printer with a 0.4 mm nozzle and checked for printing irregularities to rule out functionality mismatch in the final assembly. Since the material is viscous and prone to stringing, retraction before further extrusion must be helped by increasing fan speed to the maximum available. Additionally, the higher temperatures and polymer characteristics build internal stresses as the material is extruded hot, causing progressive layer shrinkage towards the top of tall parts. Removing the cells is recommended using pliers through a cloth to avoid damaging them. Final assembly requires sanding of the contact surfaces between the attachment rail and the cassette (both 3D printed from PLA; polylactic acid), as cyanoacrylate (superglue) will not bond reliably with some PLA filaments. Finally, the rails are inserted into the cassette and fastened to the gripper adapters using M6 bolts to the Franka Emika Gripper (0.7 kg) and M3 bolts to the cassette adapter (see Fig. 3(b)). In total the designed soft gripper weighs 0.2 kg.

B. Cell Characterization

Compression behaviour in the cells is adjusted through fillet radii and spring lengths. This can be observed by comparing top and bottom cell in the stack (see Fig. 2 and Fig. 4(b)), as the top cell in the stack is designed to close at a stiffness of 4.5 N (long springs), and the bottom at 12.5 N (short springs). Simulation of cell compression is done through Finite Element Analysis (FEA, ANSYS), in which the material is modelled as linear isotropic with a Young's modulus of 95 MPa, yield strength of 24 MPa and ensuring forces are passed into the structure along the length of the filament.

Containing the flexure only within the joints requires more internal space per cell. This is a problem since it would require extending the straight sections of the side springs, which, in case of narrow cells, would cause contact with the stabilising column in the middle of the cell. For example, if the spring element length is 7 mm or longer and the total cell width is 14 mm the cell fully compresses before the vertical column reaches the bottom of its travel. As such, FEA testing the straight cell element sizes of 5.5 mm to 6.5 mm in 0.2 mm increments reveals the potential for a substantial softening from 5.5 N to 4 N per cell, respectively, even as fillet radii are maintained. This has the benefit of a higher grasp cell resolution as more stacks can be deployed.

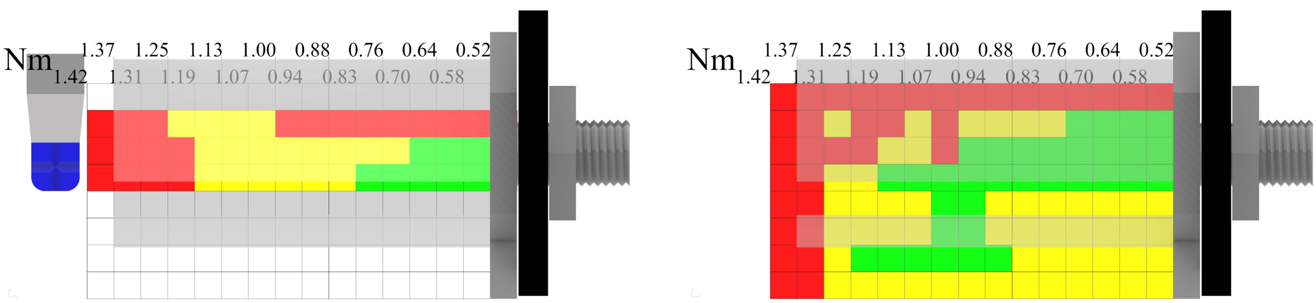
Fig. 4(a) shows the simulated and tested closure forces for the top and bottom cells in the cell stack. Individual cells are compressed to their full closure of 2.5 mm, either by FEA



(a) Simulated versus tested closure force for the top and bottom compliant cell in the stack. Results show a slight deviation from the simulation in the case of the bottom cell and a better fit in the top cell.

(b) Left image shows a Finite Element Analysis (FEA, ANSYS) of a cell stack, depicting compression in mm. Right image shows a 3D printed cell stack, compressed with 5N. Top cell reaches full, 2.5mm closure while the bottom cell reaches 1.25mm closure.

Fig. 4. Characterization and results of individual compliant cell stacks.



(a) The original gripper pads of the Franka Panda robot (top left in blue) offer only 45 grasp locations. Only grasps close to the added mass (0.5kg black disc) give good results.

(b) The 3D printed hard wide pads (see Fig. 3a) offer 120 grasp locations, however, success in grasping does not give conclusive results.

Fig. 5. Grasp results with the original (a) and hard gripper pad (b) for the turbine blade mockup (semi-transparent gray, total weight: 0.65 kg) offer worse results compared to the proposed soft gripper, shown in Fig. 6(a). Each cell square is 10 × 10 mm.

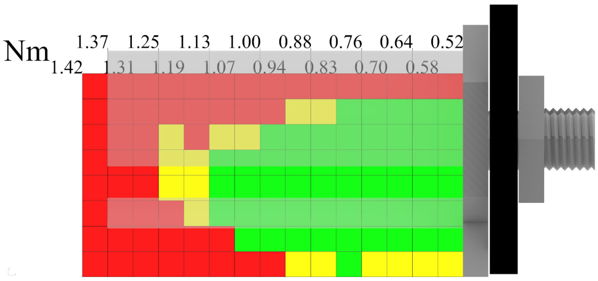
simulation and by adding real weights on the 3D printed cells. Despite slight deviation from the simulated stiffness, the trend is consistently linear and close to the margin of error caused by the discrete force application resolution. On the other hand, even a small deviation for individual cells can have a significant effect when multiple cells are deployed. For example, as shown in Fig. 4(a), the small deviation for the individual stiffer cells adds up to a difference of 17 N when 6 cells are deployed.

C. Gripper Benchmarking

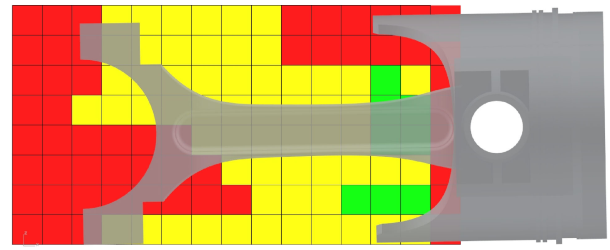
Benchmarking of the soft gripper is done through a comparison with the original, robot manufacturer provided gripper pads (Franka Panda) and a hard design version of the proposed prototype (see Fig. 3(a)). Adapters are designed to fit the original fingers of the grippers for load distribution and minimisation of torque at the base of the fingers. This reduces the flexibility caused by bending of the fingers concentrating the compliance in the cell stacks. Grasp strength is chosen as the primary performance metric with slip resistance being used to control the friction variable. A torque is applied through a weight at the end of the object (0.5 kg black disc in Fig. 5) and selecting grasp locations further away from the weight therefore generates a higher torque.

Grasp strength determines the useful payload a gripper can carry for a particular set of objects and their geometries. It also provides a measure of the pushing and pulling forces the gripper and its soft cells can resist. This is dependent on the frictional forces exerted and the coefficient of friction between objects, which in turn is dependent on the material pairs. To account for this variation and assess the gripper solely based on its functional merits, the original gripper pad is reverse engineered to use the same material as the compliant cell stacks and the hard cell version (TPC, see Fig. 3(a)). This hard cell configuration of the gripper pad is sensitive to frictional forces because it does not envelop the object completely as compared to the soft gripper and therefore applies less normal forces to the object surface. The holding torque is calculated for the turbine blade mockup and compared to the three aforementioned grippers by the (in)ability of lifting the object. For this, the distance from the centre of mass through a volume analysis in FreeCAD is used indicating a maximum of 1.42 Nm torque due to the size of the object.

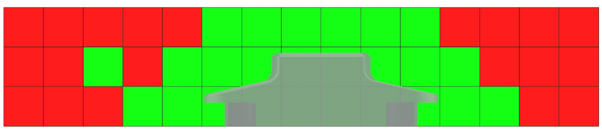
In addition, this grasping capability is assessed in terms of distance (and thus torque) around the object within which it is possible to successfully grasp the object (see Fig. 5 and Fig. 6).



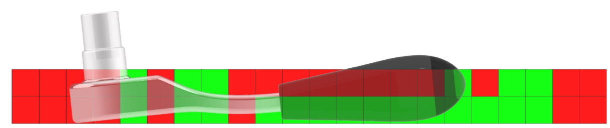
(a) The proposed soft gripper provides 120 grasp locations on the turbine blade mockup, from which a large set (53 or 44%) are successful grasps, lifts and put-down.



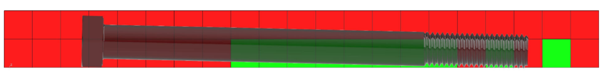
(b) The piston and conrod combination (carbon steel, 0.92 kg), results in mostly useable grasps (67 or 56%, including successful grasps), as its weight causes rotation in the soft gripper.



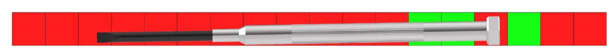
(c) The valve tappet (light and highly textured; stainless steel, 0.07kg) results in successful grasps, when most of the part is inside the gripper.



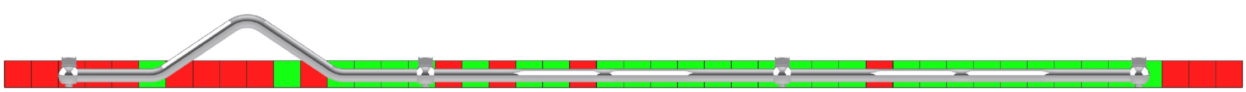
(d) The ratchet and 10mm socket (stainless steel, 0.13kg) results in successful grasps, as long as it is grasped closest to the resting surface, likely due to the rubbarised handle and its widest part being within the gripper.



(e) The M11 Bolt (stainless steel, 0.14kg) results in successful grasps, as long as it is grasped closest to the resting surface, likely due to the widest part being within the gripper.



(f) The small screwdriver (stainless steel, 0.02kg) only has few successful grasps, likely due to its size being small enough to slip in between cells.



(g) The fuel return line (stainless steel, 0.11kg) results in many successful grasps (29 or 63%), likely due to its light weight producing small moments.

Fig. 6. Grasp results with the proposed soft gripper. Green denotes successful grasp, lift and put-down, yellow denotes successful grasp and lift, but not put-down, as e.g., the object moved in the gripper, and red denotes a failed grasp. Each cell square is 10×10 mm. In total 436 grasps are performed by the proposed soft gripper with compliant cell stacks for assessment.

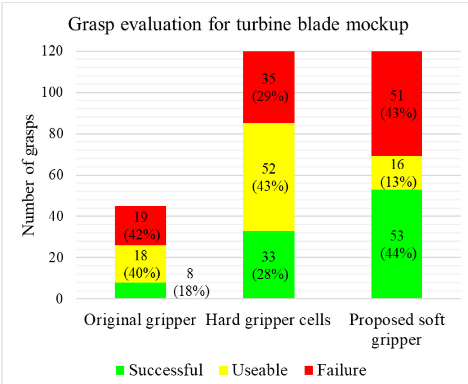
Success of the grasps is depicted in three (colored) categories: green denotes a successful grasp, lift and put-down, yellow denotes a successful grasp and lift, but not put-down, as e.g., the object moved in the gripper, and red denotes a failed grasp. Each grasp is executed once and grasp locations over the object are segmented into vertical and horizontal steps (10 mm). A fixed grasp force is set at 100 N.

Turbine blade grasp results with the original gripper pad, the hard gripper pads and the proposed soft gripper are depicted in Fig. 5(a), Fig. 5(b) and Fig. 6(a), respectively, and quantified in Fig. 7(a). Results indicate that the proposed soft gripper has a greater range (120 grasp locations in 10 mm steps) for gripping than the original small gripper pad (45 grasp locations in 10 mm steps), likely due to the small size of the soft cell stacks and the convex and concave surface of the blade. Even though the proposed gripper spans a larger area ($5 \times 10 = 50$ cm^2 footprint, with a possible $10 \times 1.6 \times 0.6 = 9.6$ cm^2 contact area) than the original pad (1.8 cm^2), the compliance of the cells ensures stability of the grasps. In addition, the proposed soft gripper has a higher success rate (i.e., successful grasp, lift and put-down; green squares) than the other two grippers. Stability in grasping is also demonstrated better for the proposed gripper by comparing the measures for holding torque (Fig. 5 vs. Fig. 6(a)). While the maximum holding torque in a successful grasp is roughly identical ($\approx$1.1 Nm), a better distribution can be identified for the proposed gripper.

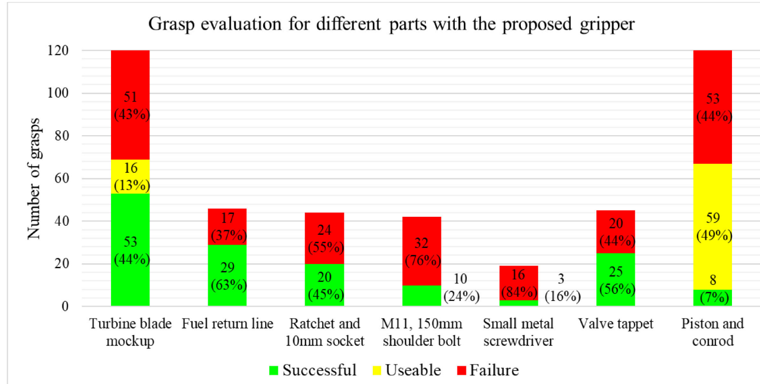
D. Grasp Testing

Blind grasp capability of the proposed gripper is also assessed with six other industrial parts. Industrial parts are chosen due to their relevance; a local Diesel engine manufacturer aims to install a collaborative robot in their engine assembly work cells and all selected parts would potentially be handled by the robot.

The success rate of gripping with the proposed gripper is depicted in Fig. 6 and quantified in Fig. 7(b). In particular, the following conclusions can be drawn from the grasp results. The curved turbine fan blade (0.65 kg including weight) is suitable for the designed compliant gripper and has a large area where blind grasp attempts result in a successful grasp (see Fig. 6(a)). Limitations for successful grasps are mainly due to the large moment further away from the center of mass. Would the mass, attached to the blade, not be added, it is expected that almost the entire blade profile would be suitable for blind grasping.



(a) Proposed gripper has a greater gripping range and a higher success rate due to the compliant cells.



(b) Results of grasping with the proposed gripper demonstrates that, depending on the grasp location (see Fig. 6), complex objects can be successfully grasped.

Fig. 7. Grasp results for different grippers (a) and different objects (b). Green denotes successful grasp, lift and put-down, yellow denotes successful grasp and lift, but not put-down (e.g., the object moved in the gripper), and red denotes a failed grasp. Note that each of the 609 grasps has a unique grasp location (see Fig. 6) and repetitive grasp attempts on the same grasp location are reliable and gave the same result.

The piston and conrod combination is the heaviest part (carbon steel, 0.92 kg) with grasp locations only at the conrod (see Fig. 6(b)). While the majority of grasp results indicate successful grasp and lift, the object moved inside the gripper due to the heavy piston centered on one side. As this motion is not sensed, placement of the object at a desired location would not be possible. Despite this, grasping is still useful in a human-robot collaborative scenario, where the robot could hand-over the part to the human.

The valve tappet grasps demonstrate good results, when a larger part is situated inside the gripper (see Fig. 6(c)). This is most likely due to the size and shape of the part; wide, light and highly textured (steel, 0.07 kg). Similar results are found for the fuel return line (stainless steel, 0.11 kg), which, despite its length, is easy to lift due to producing small moments (see Fig. 6g). The compliant cell array stabilizes the part through multiple points of contact even though it is not being grasped at its center of mass.

The remaining three parts, i.e., the ratchet and 10 mm socket (stainless steel with latex handle, 0.13 kg), the M11 bolt (0.14 kg) and the small screwdriver (0.02 kg), both stainless steel, largely demonstrate a clear cut-off between success and failure (see Fig. 6(d), Fig. 6e and Fig. 6(f), respectively). Low locations and those outside of protrusions are more suitable for grasping, as the cells have more surface area to grasp low friction surfaces. However, these are not consistent over the length of the part. This is most likely due to the shape of the part (long and thin), meaning they can slip out or in between sets of cell stacks.

Results reveal that grasp attempts for different parts can be divided in two classes; 1. Parts that are large with complex shape, resulting in successful grasps, lifts and (if not too heavy) put-down, and 2. Parts that are small or thin often result in successful grasps, lift and put-down, only if the compliant cell stacks can conform around the part. In both cases success or failure can be explained by either having sufficient or insufficient contact points from the compliant cell stacks.

IV. Discussion

Related work of soft two [11], [12], [14] and multi-fingered grippers [10], [13] overlaps in terms of optimising handling goals, where an increased surface area of the grasp provides a more secure grip. One difference between our approach and other soft grippers, is the intended objects to grasp, as we aim for industrial parts and most other works focus on household objects or food items [10], [12]–[14], [19]. In terms of actuation, our soft gripper is mounted on a cobot (Franka Panda) and uses its gripping mechanism with 100 N grip force. As a result, the maximum lifting capacity is around 1 kg. Other works can support near 2 kg [13] or up to 11.3 kg [14], however, rely on pneumatics thereby introducing additional requirements to the production environment. Moreover, in both works the object center of mass (COM) needs to be inside or underneath the gripper, whereas our design can grasp objects with a COM outside the gripping area.

The compliant cell stacks in our soft gripper are designed for blind grasping, whereas other soft grippers utilize sensor information for better grasping [9] or for object identification [19]. Our proposed gripper creates multiple points of contact between the cell stacks and the object and thus circumvents the need for accurate sensing techniques that estimate an object pose for grasping. However, the blind grasping approach results in an unknown, or poor estimate of the object pose with respect to the gripper, which leads to few consecutive manipulation possibilities after grasping. For example, automated, accurate object placement or assembly would be problematic, if no additional sensing is included. Therefore, the proposed approach is motivated for human-assisted manipulation, such as human-robot or robot-human handovers or assisted (dis)assembly procedures.

Design for manufacturing requires consideration of the dimensional limitations of the 3D printer. For example, the width of the extruder determines how flexible the thinnest joint can be. As it is possible to decrease the nozzle size from 0.4 mm to 0.15 mm, this would allow smaller and softer cell stacks and could therefore increase the number of cells per gripper pad for a similar force profile. Such smoother surface of soft cells would create more contact points for potential better object handling. In addition, the minimum thickness of a flexible hinge can be circumvented by using a multimaterial extruder as in the case of Kinetix [24]. Provided there is good inter-material adhesion, a softer hinge can be attached to the joints of the structure and the overall size of the cell can be reduced.

Fatigue of the gripper and the compliant cells has not been observed during and after experiments, and all 609 grasps have been made with the same finger adapter, cassette and cell stacks. However, wear on the compliant cell stack contact surfaces is apparent, and the 3D printed surface is lacerated, likely increasing the coefficient of friction between the cell array and the object.

V. Conclusion

This work proposes a novel soft gripper design based on 3D pinted compliant cells. The design is motivated by the grasping of complex shaped objects such as jet engine turbine blades or Diesel engine components, for which traditional gripping approaches (i.e., stiff parallel grippers) are unsuitable. The compliant cells introduce controllable flexibility and conform to the object shape, thereby distributing the force evenly and reducing the need for accurate grasp pose estimation. Characterization of individual compliant cells, stacked cells, as well as cell arrays demonstrates the capabilities of the gripper design. Extensive experimental evaluation of $>$600 grasps with seven different industrial parts and tools and comparison to two traditional grippers demonstrates the effectiveness towards industrial use. Results demonstrate that the proposed soft gripper is most suitable for handling complex shaped objects, such as the fan blade and piston with conrod, where the shape of the object enables the compliant cells to compress individually. On the other hand, the grasping of small, narrow and long objects is only successful when the compliant cells can conform around the part. Future work will focus on miniaturizing the size and stiffness of the compliant cells to allow a higher resolution gripping surface, sensorizing the cells and targeting other application areas, such as non-rigid objects in food industry.

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