Squeeze-in Functionality for a Soft Parallel Robot Gripper

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Abstract— **Grasping parts of inconsistent shapes, sizes and weights securely requires accurate part models and custom gripper fingers. Compliant grippers are a potential solution; however, each design approach requires the solution of unique problems. In this case, the durability and reliability of half lips (at least 1400 cycles) to perform consistently as springs of a specified stiffness (0.5N/mm) and displacement (5mm). Moreover, the challenge of low and small (3mm, 0.01kg bolt or Allen key) objects is addressed through vertical squeeze-in, implemented using an incline, lip and flex limiter as part of a 3D printed TPC spring. The squeeze-in phenomena are verified on large objects through a 30mm, 1.66kg common rail. Experimental results demonstrate the reliability when given a human-specified location for gripping, without the need for jigs or fixtures. Finally, the tested design is assessed for potential fulfillment of 7 of the United Nations sustainable development goals.**

I. INTRODUCTION

Secure grasping of small and large industrial components is difficult to accommodate with a single gripper. Robots in industrial work cells therefore use a feeder mechanism, handle a single or similar parts or change the gripper of the robot while in continuous operation [1]. As industries move away from the manufacturing of standardized to custom products, and encompassing solution for part variability is needed [2]. Currently the lack of versatility is compensated by breaking down the assembly process into individual stations handling a single step at a time, leading to manual assembly as the default solution. For example, low production volume Diesel engine assembly involves grasping of large engine parts and small components such as fasteners and bolts with the same robot, requiring careful design of the work cell and the component feeding systems. A collaborative scenario between a human and a robot can potentially offer a more efficient assembly process, compared to manual assembly, and higher reliability, compared to a full robotic solution. In such human-robot collaborative case, a robot could hand-over smaller parts to the operator or hold larger parts in place, while the operator completes an assembly step [3]. Robots and robot grippers should therefore be able to handle a larger variance of workpiece sizes in a different assembly order while taking less floor space alongside parts typically designed for human manipulation, such as tools (see Fig. 1).

This paper presents an improvement to a compliant finger design [4] by way of raising previously impossible to lift small Allen keys and common rail. The fingers can be fitted to a standard robot parallel gripper mechanism, and hence use the robot gripping mechanism for actuation. The entire gripper fingers including the compliant cell stacks are 3D printable, whereby the compliance and squeeze-in functionalities are obtained through the flexible 3D printing material. To summarize, the proposed finger design should offer the following benefits:

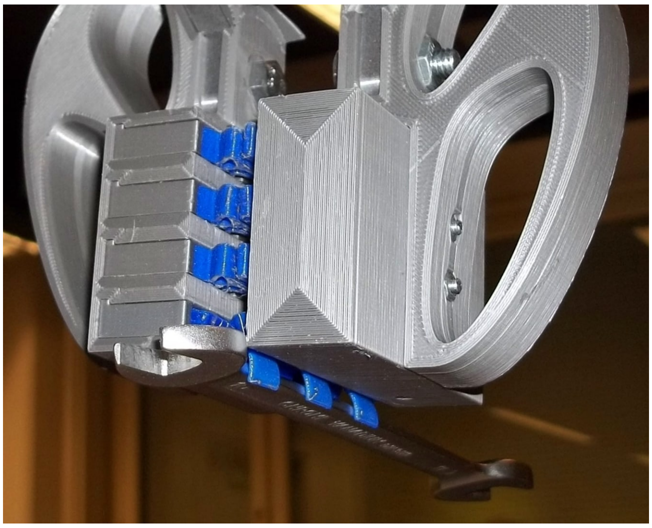

Fig. 1: The proposed gripper demonstrating the squeeze-in functionality by grasping a wrench tool. Compliant cells (blue) can deform around an object, whereby the lowest row of cells have lips to enable the squeeze-in functionality.

- A large compliant surface for grasping parts to distribute the grasp force evenly over the surface.
- The gripper finger design with squeeze-in functionality deforms during gripper closure to lift low parts from a surface.
- Handling small and large parts without an externally stabilised grasp pose by jigs or fixtures.
- Fitment to a standard parallel gripper and utilizing its actuation mechanism, without external devices.

Functionality of new features should be demonstrated by grasping industrial parts and tools. In particular Diesel engine components such as a common rail and fuel lines (see Fig. 2a) alongside parts such as bolts and hand tools (see Fig. 2b). For this, the proposed gripper is mounted on a collaborative robot (Franka Emika) and parts are grasped with a fixed grasp force of 100N.

The paper is organized as follows. The paper is introduced in the Section I. A brief overview of the current developments in grasping technology is given in Section II, which describes the advantages and limitations of existing gripper designs.

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(a) Diesel engine common rail with fuel lines. Square size: 1cm^2

(b) Bolts and hand tools

Fig. 2: Different parts and tools considered for the gripper. Parts are both large (a) and small with low profile height (b).

The object grasping problem motivation is addressed in Section III and the proposed gripper design is described in Section IV. Results are presented in Section V following repetitive grasping with 14 parts and a review of the sustainability practices in manufacturing and a discussion on its grasp performance. Section VI summarizes the outcomes of the analyses in the context of previous literature.

II. RELATED WORK

Current developments in grasping technology are presented through examples of the trends in gripper designs, purposes, goals and limitations.

A. *Hard Grippers and Fingers*

Hard robot grippers and fingers are the current standard in industry and are typically supplied with the end-effector of the robot manufacturer [1]. Their rigidity, combined with close tolerance assembly provide large handling forces. Honarpadaz et al. present a design, whereby the large holding forces are retained but improve on the surface area for holding workpieces [2]. The process involves converting a CAD or surface model into a mesh, and then into a point cloud to determine the amount of contact points and force normals. This information is then used to select a grasp orientation and later surface shape to accurately match the shape of the object. The process is repeatable and capable of matching multiple objects onto a single gripper, as well as finding the mean shape providing the most grasp area for all objects involved. A similar approach by Wolniakowski et al. samples the workpiece CAD surface file but also accounts for the material, mass and inertial qualities of the object [5]. While it does not account for the handling of multiple objects by the same gripper, as in a workpiece and feeder scenario, it can work in a more unstructured environment whereby object placement and obstacles can be an issue.

A limitation of the Honarpadaz and Wolniakowski methods is their suitability for factory automation where the known workpieces are assembled by a robot at an assembly line. The automation or design engineers must have access to the CAD files of the objects to automate and manufacture the design ahead of time. In the cases where the workpiece does not match the gripper surfaces at locations they provide support, sliding can occur. This is taken into account by Khamis et al. who propose an array to detect slip inside fingers or contact areas [6]. Detection works through light sensors detecting the amount and pattern of pillar bending.

Other work proposes a rigid gripper with pull-in functionality enabled by a sliding sheet [7], which is actuated by a passively mechanism that slides the thin surface inwards. Experiments demonstrate the gripper picking parts such as bolts, paper and tea bags.

B. *Soft Robot Grippers and Fingers*

The most promising soft technology for small and low objects is the 'Universal Robotic Gripper' that utilises granules encapsulated by a balloon to envelop or adapt to multiple objects [8]. Grasping works on the principles of jamming (enveloped by the hardened state of the gripper similar to hard fingers), friction (wrapping the object for increased surface area) and suction (object is smooth enough not to allow air to enter under the balloon and allows the surface to completely stick to the granules), and a wide variety of part grasping is demonstrated.

Most commonly, however, soft robots utilize distinct fingers [9], [10]. This allows easier control over the object compared to balloon grippers with their almost infinite degrees of freedom. Adjustability is enhanced further as in [11] where bending sensors are fitted to detect the extent and location of flexure, while providing the robot with the capability to adjust its grasp. Other enhancements include optical fibers to measure bending and detect the shape of an object [12] and gecko adhesive fingers that lift difficult objects through attractive forces [13]. Together these technologies have the capability of providing high holding forces for (industrial) objects, given the possibility to wrap around an object.

A common working principle for grasping with soft fingers or end-effectors is therefore pneumatics or hydraulics. This introduces additional complexity to the work environment and requires space for the fluids to travel in, thereby making their adoption more difficult than running the end-effector and fingers off electricity. Movement can, however, be provided by dielectric finger gripper alloys which can be sheet thin to slide under the workpiece [14].

C. *Combinations of Hard and Soft Grippers and Fingers*

Combinations include soft and rigid members in the gripper or finger assembly. This approach has the benefit of accurate control over the bending in specific directions. For example, Chavan-Dafle et al. propose pneumatically actuated fingers that change shape to enable the orientation of cylinders without movement of the end-effector or the rest of the robot [15]. The rigid members employed change from a V to a wedge to increase contact area between the cylindrical object once it has been turned vertically.

Advances in rapid prototyping allow the creation of sections that are distinctly different in rigidity, within the same structure, as demonstrated in [16]. For example, multi-material 3D printing allows the placement of urethane joints between rigid members. This enables the computational design of structures by constraining flexure only in desired areas. Principles described by Howell [17], as well as Zentner and Linß [18] can be employed to accurately constrain this movement, without backlash, for use in high-precision systems such as satellite thruster orientation. Grippers utilizing this technology are presented in [19], [20] and [21].

Compared to the related work, the design proposed in this paper has the following properties. First, our proposed gripper has two distinct functionalities: 1. compliance by a discrete set of cell stacks as gripper fingers, and 2. squeeze-in functionality for low-profile parts by lips on the cell stacks. Second, the design utilizes the gripper mechanism present on the robot and does not require external actuation, such as pneumatics. Following, these are described in more detail.

III. PROBLEM MOTIVATION

The problem considered in this paper is as follows:

1) **Single gripper for big and small objects –** Demonstrating grasp characteristics and phenomena alongside reliability in handling of small and big objects.
2) **Small objects with low profile –** Industrial tools and parts (e.g., hand-tools, bolts) are not designed for robot picking. As their low profile is close to the resting surface, a different solution for grasping is required.
3) **Sensor-less grasping –** Object pose estimation can, in many situations, not always be reliably guaranteed and so grasping should be possible without sensing.

This problem statement stems from industrial scenarios where object handling is typically executed with help of feeders or object fixtures ensuring high-accuracy of placed workpieces. Factory environments facilitate the work of the robot by; handling a single or few types of parts, or provide the opportunity for gripper or finger changeovers. The fingers in this paper are designed for a scenario where; objects have a broad variation, low profile height and are not placed in a predefined location (see Fig. 2). The goal of this paper is to extend the testing of prior work [4] by the introduction of features for improving low object grasping and assess the reliability of flexible finger features smaller than 1cm.

The developments are done to improve human-robot collaboration in manufacturing. In this regard, a handover process utilising minimal sensing and limited coordination modelling is considered the simplest way to enable interaction. Object hand-over from robot to human and human to robot has been investigated in the past [3], in order to coordinate the hand-over by different signals and cues. The first step towards interaction simplification is by utilising the pliance of a gripper to compensate for the absence of sensing.

TABLE I: Squeeze-in gripper technical requirements

Feature	Value
Largest object part dimensions (L×W×H)	$400 \times 30 \times 80$ mm
Smallest object height[1]	3 mm
Gripping force	100 N
Maximum lip deflection	5 mm
Maximum object weight[2]	2.0 kg
Minimum lip length[3]	2 mm
Minimum printable detail thickness[4]	0.8 mm

1- Smallest object height that can be lifted from a surface
2- Limited by the robot payload (3kg) - gripper weight (1kg)
3- Lips longer than this extend past the gripper
4- Default limitation of slicer software

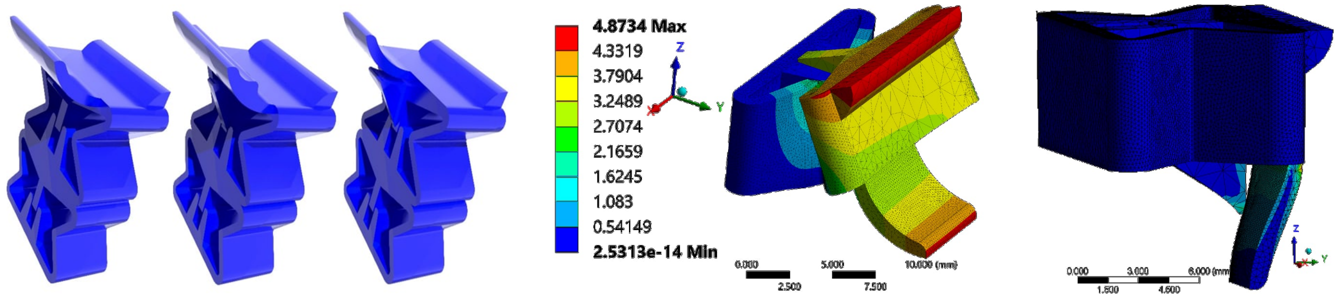
Besides functional requirements of the fingers, the technical requirements drive its physical design. In particular, Table I lists several technical requirements which are crucial to achieve the desired outcome of blind grasping. Notably, requirements such as the gripping force, payload and object dimensions, are due to the limitations of the robot and its gripper actuation mechanism.

IV. DESIGN

A combinatory design approach is chosen, incorporating rigid and soft grasping structures as found in the human hand. Here, grip is dependent on the fingerpulp capability to deform around the grasped object and is limited by bone [22]. Similarly, slip is undesirable and avoided through the lip features supporting the work-piece through friction. The soft gripper is designed to take the same approach, whereby soft cells provide increased surface area and deformability only around the grasped object. This retains a low amount of unaccounted for degrees of freedom and allows forces to be transferred to the object for stable grasping.

A. Cell Anatomy

The compliant cell stack design described in earlier work [4] concludes that full compression of one cell stack occurs at 12.5N and half-closure of the gripper (20 cell stacks) at 90N. Additions to this design include an incline, lip and a lip flex limiter for each cell stack in the lowest row of the gripper (see Fig. 3 and Fig. 4b). This enables the grasping of low objects by squeezing-in objects into the gripping surface. Similar to the original cells compressive limiters, hard stops are introduced under the lips to achieve jamming, limiting the movement without impeding the cell compression stroke. The incline forces the cells to bend upwards, while the 5mm long lip is used to slide as low as possible along the work surface and scoop the object. The size and stiffness of the lip defines which low profile objects can be squeezed-into the gripper and picked up. The half lip configuration (see Fig. 3a) that is 5mm long with 5mm arc radius and an incline that is 1.5mm long and 2mm high. This design is the best trade off between collisions with the table during squeeze-in, lip grasp force strength, and incline overlap when handling small bolts. A 5mm lip length implies that when the lip makes contact



(a) Different lip designs for the squeeze-in functionality of the soft gripper: regular lip (left), riser lip (middle) and half lip with limiter (right).

(b) FEA of the compliant cell with lip depicting vertical scoop in mm upon an applied force to the incline.

(c) FEA of the compliant cell with lip depicting bending upon an applied force to the lip.

Fig. 3: Cell design combines Finite Element Analysis (FEA) for determining the behavior upon an applied force.

with the surface, a gap of 3mm remains between the gripper and the surface (see Fig. 4c).

B. Simulation

The half-lipped variation is assessed via the simulation of cell compression, depicted in Fig. 3b-3c. This decreases prototyping stage time and can be considered virtual testing done through Finite Element Analysis (FEA, ANSYS), in which the material is modelled as linear isotropic with a Young's modulus of 95MPa, yield strength of 24MPa and elongation at break of 530%. It offers an easier method of feature functionality verification circumventing the need for access to a real robot and fine camera work. The desired flexural behavior of the lip and cell can be finely adjusted for the type of assembly parts expected for grasping. In the case of the half lip design, simulations demonstrated a 4.5mm deflection of the tip as the middle section contacts the lip flex limiter. Simulations further reveal a highly stressed point of concern at the base of the lip of 41MPa, nearly double the yield strength with an accompanying elongation of 0.54mm.

C. Gripper Configuration

As the configuration of the gripper is similar to our previous work, we refer to [4] for a detailed design description. However, to enable the squeeze-in functionality, a different distribution of cell stacks per gripping surface is utilized. A total of 20 cell stacks is used (10 per side), where the cell stacks closest to the grasping surface are cells with lips (3 per side, see Fig. 4b). Low and wide profile imply 6 cell stacks can be in contact during grasping, distributing the 100N of grasp force. Fig. 3a depicts different designs to the lip configuration to achieve a desired behavior. All variations have the new introduced incline, which adds the scooping characteristic. The first is most capable in picking up large, flat and heavy objects through the availability of larger contact surface and therefore increased friction to reduce slip. It struggles with providing enough contact area for the small objects used in testing. The second adds a bump, attempting to reduce slip. The third and final solution features a flex limiter, helping to lift the large objects and increases the features and surface area available for the grasping of the small objects.

V. RESULTS

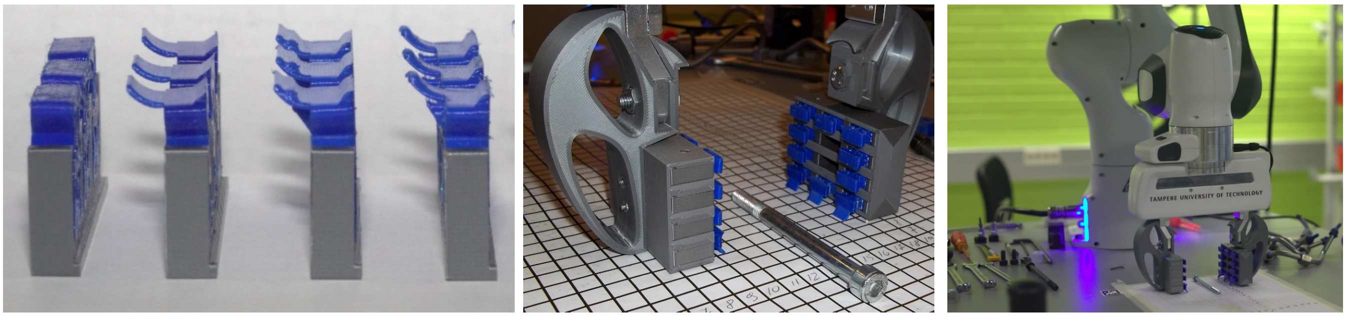
Results relating to the prototyping and manufacturing steps are presented in terms of sustainability in the context of the United Nations 17 sustainable development goals (SDG), as well as reliability and gripper finger fatigue in terms of grasps.

A. Prototyping

Preventive maintenance improves operational time and decreases price. This is achieved through FEA analysis which will establish maintenance conditions in terms of an operational period for the flexible soft cells once material performance data is obtained. Insecurity and disruptions to manufacturing processes made using the gripper fingers are lowered by the possibility for deferred manufacturing when maintenance is needed. Because the finished finger parts inventory is low, material can be stored in undifferentiated form. This brings the advantages of reduced environmental degradation and lower storage costs. Faster turn around times are achieved by simplicity of editing and making the needed parts on the same machine. For example, replacing a damaged cell stack (16 min. printing time) or rail with three cell stacks (72 min. total printing time) can be performed by technicians close to the FEA suggested conditions. (SDG; 8, 9, 12)

Additive manufacturing enables reshoring to reduce use of oil in transportation and production. The 3D Fused Deposition Modelling printer of 700 euro can be used to make all the gripper finger parts, rendering transportation between countries unnecessary. In-house manufacturing with electricity and the geometrical adaptability of lip geometry makes dependence on external contractors in centralized industrial zones unnecessary. The price of materials (30 euro for 0.5kg of TPC and 1kg of PLA) makes production cheap and ecological due to the minimal amount of waste. Prusament Polylactic Acid (PLA) is completely industrially compostible, and the FormFutura Flexfil (TPC) contains 43% renewable organic content. (SDG; 11, 12, 13)

Open source enables development at the design stage using FreeCAD (`https://www.freecadweb.org/`). It makes physical, concurrent development possible internationally without the burden of lead times and dependence



(a) Individually 3D printed cell stacks. (b) Gripper and cell stack configuration. (c) Final robotics system used in testing.

Fig. 4: Results of the prototyping stage; the 3D printed cells (a), the gripper configuration (b) and the grasp test setup (c).

on specialist tools, labour and logistics. Everything in the project will eventually be manageable through the bundled add-ons. (SDG 17)

Fig. 4a shows the 3D printed cell stacks with and without lips that are utilized in the proposed soft gripper. The half lip design was utilized for experiments. Fig. 4b shows the gripper configuration and the distribution of the cell stacks within it; only the lowest row of cell stacks have lips for the squeeze-in functionality. Cells with lips close at the same force due to the side-spring geometry in the cells not being changed from the original design [4]. The difference is, cells reopen at the top of the compressive pillar when lips provide the majority of the holding force. Alternatively the bottom of the compressive pillar opens if the object is squeezed in by the inclines, or the lips are pushed in by the gripper.

B. Grasp Experiments

For grasp assessment, the Franka Emika collaborative robot is used and the proposed soft gripper is attached to its existing gripping mechanism (see Fig. 4b and Fig. 4c). In grasping literature, different metrics are currently being used to assess the quality of a grasp [23]. Moreover, since 2018 test procedures and definitions attempting to standardize testing have been published by NIST [24], [25], which targets performance metrics for individual gripper efficiency and collaborative work. Most of these metrics are ill-suited to the use case because they do not take into account industrial object shape variability.

In more detail, the NIST recommendations are focused on gripper functionality, are multi-faceted and include: finger and grasp strength, slip, cycle time, efficiency and manipulation. To be a valuable asset in maintenance or manufacturing, however, the useful life or durability of the gripper are a necessary dimension. The difficulty in assessing it stems from the use of TPC as spring material. Because compared to metals, TPC functionality hinges on flexural memory rather than not exceeding a high yield strength. While elongation at break (530%) and yield strength (24MPa) are provided, a stress-strain graph and fatigue data is unavailable. Since the point of concern is the large moment arm of the lip.

In this work, the grasp experiment focus is on establishing safe grasp cycle limits of the highly stressed lips. Repetitive grasp experiments are done by placing a part underneath the gripper without predefined pose and executing a grasp motion sequence 100 times consecutively with a set grasp force of 100N for each work-piece. The gripper is assessed by observing whether the parts are picked up, lifted and put down without a detected collision. It should be noted that the workpiece position is set manually, i.e., grasping is executed blind. A video of the grasp experiments can be found through the following link: `https://youtu.be/NpYcp82-Nak`.

C. Grasp Assessment of Larger Parts

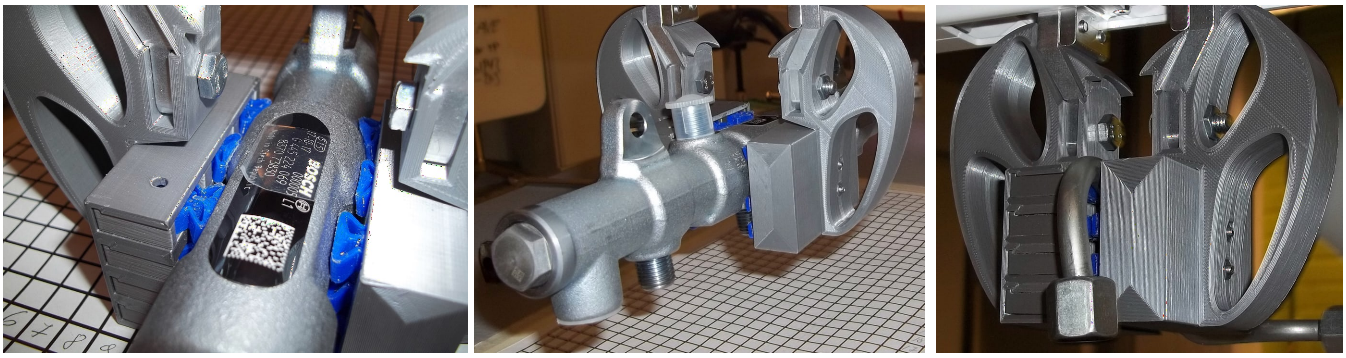
The set of larger parts consists of a Diesel engine common rail (1.66kg) and four fuel lines (0.11kg each), depicted in Fig. 2. Grasp assessment of these parts serves to verify that the lips on the lowest cell stacks do not influence the behavior of the original cell stacks and the overall functionality of the gripper. Experiments consisted of a total of five grasp cycles (100 grasps per series for each of the five parts) of which none failed (500 total repetitions), as long as the parts are roughly placed on the centre-line. Fig. 5 shows a selection of grasp results for the larger parts, i.e., the Diesel engine common rail and one fuel line. In particular, Fig. 5a shows that the compliant cells deform around the part, thereby securing sufficient contact points for a stable grasp.

D. Grasp Assessment of Smaller Parts

The set of smaller parts consist of a selection of different sized bolts (M3, M5 and M8) and hand tools, such as two spanners (0.05 and 0.12kg), a ratchet (0.12kg), a small screwdriver (0.03kg) and two Allen keys (0.01 and 0.05kg). The diameter of these parts are as small as 3mm, meaning the lowest profile for grasping is also 3mm.

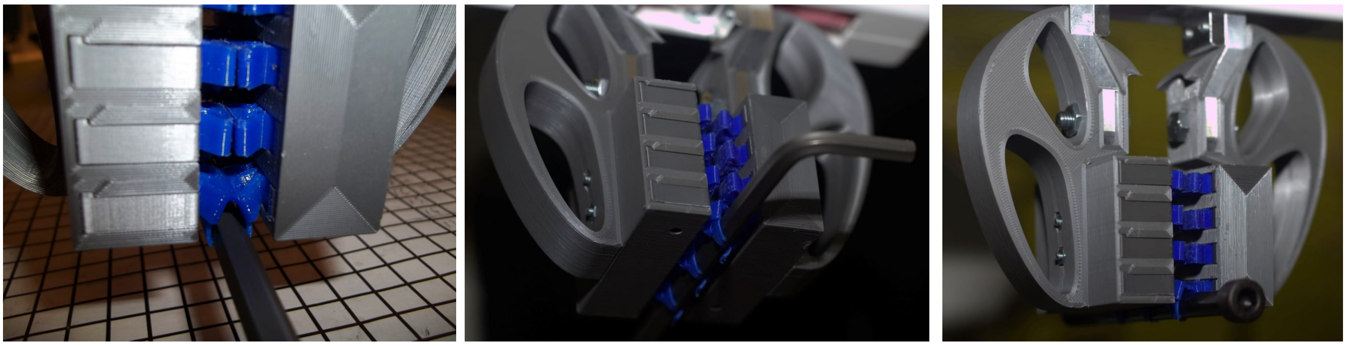
Experiments consisted of a total of nine grasp series (100 grasps per series for each of the nine parts) out of which none failed (900 total repetitions), as long as the parts are roughly placed on the centre-line.

Fig. 6 shows grasp contortion while lifting the tools and bolts which have a low profile when resting on a surface. Fig. 6a in particular shows that the cell stack deforms while the lips are held in place by the lip flex limiter as designed and depicted in Fig. 3a. Limits to the original gripper finger functionality is found around a profile height below 3mm, for which the grasping is longer reliable.

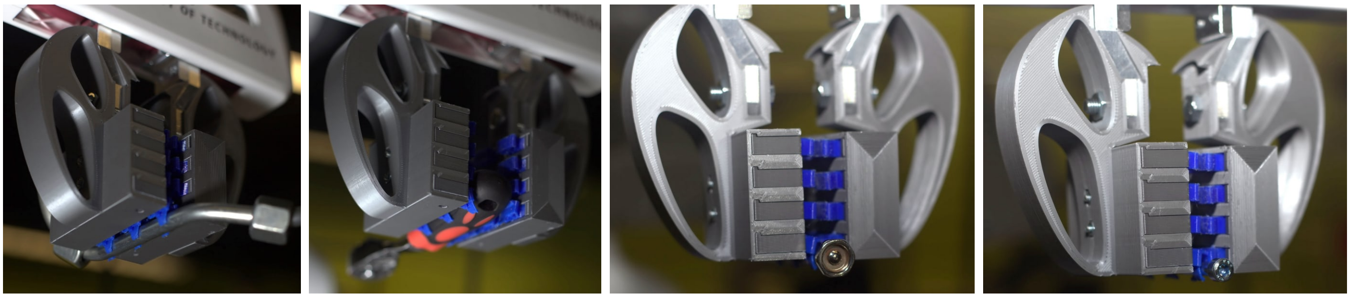


(a) Cell stack deformation to large object (b) Common rail (c) Fuel line

Fig. 5: Grasping results of larger parts demonstrates that the lips do not influence their grasping.



(a) Cell/lip deformation to low profile object (b) M8 Allen key (c) M8 Bolt



(d) Fuel line (e) Ratchet (f) Small screwdriver (g) M6 Bolt

Fig. 6: Grasping results of low profile parts demonstrates that the squeeze-in functionality leads to successful grasping.

E. *Discussion*

While no failure is observed and a degree of grasp capability can be derived, the most important aspect of the tests is determining there is no performance degradation due to repeated use. With 1400 executed grasps and complete success rate, it is concluded the lips, incline and flex limiter can reliably perform. In addition, an advance in the capability of the fingers to grasp objects with a 3mm height is observed, previously impossible with the flat surfaced cells depicted in the leftmost position of fig. 4a.

Print success rate of the cells remains the same as that of the original cell stacks [4]. While there is a noticeable quality decrease with the half-lipped cell stacks, functionality during grasping is unhindered. Adding full lips to the cell stacks yields no warping, while a smaller printing nozzle is likely to resolve and enable smaller lip sizes for future iterations.

Finite Element Analysis (FEA) is time consuming, despite the small amount of nodes in the cell mesh. This is owed to the complexity of recognizing non-linear, friction-less contact in the context of a transient structural study. In particular, the fine time stepping required produces a peaky workload where the results and skewed mesh of the previous step needs to be reloaded into RAM. The process can be sped up significantly by either using a GPU with sufficient VRAM or an AVX512 enabled CPU. Nevertheless, utilizing FEA analysis speeds up the cell design process by determining the vertical cell stiffness, allowing the collision thresholds of the robot to be adjusted accordingly.

By evaluation of the grasp results it can be concluded that the proposed gripper can grasp both larger parts (Diesel engine common rail) and small, low profile parts (e.g., Allen keys). Limitations of the design were found for parts that are low in profile but short in length, such as nuts. In these cases a part would not have sufficient contact points for a stable grasp or the part would slip in between the cell stacks.

Consecutive grasp assessment relies on a high repeatability of the robot. As the lips of the soft gripper slide across the surface when grasping, a slight difference in height might cause the lips to either get stuck (too low robot position) or not be engaged with the surface and fail to squeeze-in a part (too high robot position). This is accounted for by setting the same coordinates, rather than a return to the same pose. Because the Franka Panda repeatability is ±0.1mm), care should be taken when adopting the gripper for other robots with lower repeatability or accuracy.

In the field of soft robot grippers the common goal is versatility in terms of handling multiple objects, achieved by compliance in the fingers [10]. In industry, however, softness has recently come of interest [1] and most designs utilize rigid gripper fingers [2] that can only handle objects the fingers are designed for. Exceptions can be found for bin picking tasks, where granular jamming has shown success [8]. The approach in this paper tries to target the grasping of industrial parts and tools that are typically handled by technical personnel, thereby potentially offering robotic assistance for assembly tasks. Another difference of the present approach is the actuation mechanism for the gripper, which, in our case, utilized the robot gripper. While this is not a novelty in itself, most other endeavors require a dedicated actuator for their gripper mechanism such as pneumatics, cable driven or Shape Memory Alloys [10].

VI. CONCLUSION

This paper explores and demonstrates the squeeze-in functionality and durability of a soft parallel robot gripper. The functionality of the gripper is inspired by the trend towards human-robot collaboration, specifically human-robot handovers. Successful grasping experiments are performed for an industrial object set ranging from a M3 bolt and a ratchet, to a diesel common rail (1.66kg). The set workpieces are manually aligned for the robot to grasp, lift and place back. The small work-pieces of 3mm height added to this experiment demonstrate the lips, incline and flex limiter to be an extension to previous work that can be reliably mounted to a standard industrial or collaborative robot. The design and testing process is assisted by simulation (FEA analysis) revealing no deterioration in at least 1400 grasps or cycles which can be used as a predictive maintenance condition. Further identified are a spring constant of 2.5N/mm and a maximum stress point with 41MPa and 0.55mm of deformation for the lip, a consideration when trying to determine usability of lifting small and heavy objects in further applications. The design and testing methods can be quickly re-applied when material data is available to determine final fatigue life in the future. While the cheap and simple additive manufacturing process utilises bio-degradable PLA, and TPC with 43% bio content, combined with rapid manufacturing, aligning the fingers to the United Nations Sustainable Goals 8, 9, 11, 12, 13 and 17.

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