DEPARTMENT OF MECHANICAL ENGINEERING

Research Report

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Hybrid End-effector Concept

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ABSTRACT

Robotic end-effectors are increasingly being deployed within industrial settings to automate mundane and repetitive tasks away from human labour. Leading industry's adoption has been the use of bespoke end-effectors designed for specific tasks in reproducible environments, but work remains on creating end-effectors suited for more general-purpose tasking.

Current literature has made few attempts to synergise both suction and fingered grasping into a single design. Of the few existing attempts made all conclude further optimisation is likely to prove successful in creating a general-purpose end-effector.

This work has consequently seen the identification and design of five features of an end-effector that uses both suction and fingered grasping, optimised for general-purpose tasking. The proposed design uses tendon actuation to provide underactuated fingered grasping and mechanically self-sealing suction cups. A linearly actuated planetary gearing mechanism is designed into the palm of the end-effector allowing rotation of two of the three fingers to accommodate a wider range of grasps. Finally, a novel fingertip mechanism is also devised to adapt to the contours of geometrically complex objects.

To determine the success of the optimised design an idealised bin-picking scenario is devised; the process of repeatedly picking items out of small cluttered plastic bins. The performance of the optimised end-effector is subsequently measured against the performance of using only grasping and only suction.

The resulting design is expected to validate the hybrid approach and pioneer a new category of end-effector that can outperform existing end-effector designs, and hence accelerate the automation of general-purpose tasking.

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NOMENCLATURE

N	Normal force
μ	Static coefficient of friction
m	Mass of the object
a	Acceleration of the object
n	Number of contact points
g	Acceleration due to gravity
P_{atm}	Atmospheric pressure
P_{vac}	Vacuum pressure
r	Internal radius of the suction cup
$F_{suction}$	Force generated by the vacuum within the cups
F_{force}	Frictional force generated by the reaction force applied normal to the contact point of the finger
F_{form}	Force generated by the rigid flange supporting the object

1 INTRODUCTION

1.1 BACKGROUND

An end-effector is a device commonly mounted at the end of a robotic arm that interacts with the environment around it, often performing a task. These devices are key components within industrial robotic installations, with usage across a number of industries from automotive to food and beverages [1]. Leading industry's adoption has been the use of bespoke end-effectors designed for specific tasks in controlled environments. Prolific examples include part assembly, spot wielding and machining [2]. These devices enable users to reduce costs and enhance productivity [3] by automating mundane and labour-intensive tasks.

Despite a general increase in robotic instillations over the last decade, in recent years the rate of adoption by the world's largest markets has begun to slow [1]. This saturation has been driven by current robotic solutions inability to tackle more challenging problems. Canonical problems within robotics such as picking a variety of objects from cluttered environments have yet to be solved with accurate, efficient and reliable solutions. As a result, many industries struggle to automate more general-purpose tasking. These problems differ to predecessors, instead requiring dexterous manipulation and robust grasping of a variety of objects in undetermined environments. A common example found in warehouses is the process of bin-picking, where an individual repeatedly picks objects out of small cluttered plastic bins.

Figure 1: Images of a warehouse workers tasked with bin-picking, currently considered too difficult for a robot end-effector to automate. [Courtesy of Shelving.com]

Solutions to general-purpose tasking are often more multi-disciplinary, requiring expertise in end-effector design, computer vision, motion planning and robotic grasp planning [4]. Over the last decade, progress has been rooted in the field of computer vision and dexterous manipulation algorithms. This has been aided by the emergence of deep learning, plentiful compute-power and large datasets [5]. A recent example of this is the research conducted by OpenAI, who developed an algorithm that could train itself to manipulate a general-purpose anthropomorphic robot hand to solve a Rubik's cube [6]. Milestones such as these provide strong precedent that a comprehensive solution is on the horizon, however, similar feats have been lacking in the field of end-effector design.

Between 2015 to 2017 e-commerce giant Amazon ran the Amazon Picking Challenge (APC), offering a cash prize to competing teams in hopes of seeing innovative solutions to the pick-and-place problem [7]. Analysis conducted on the first APC found participants highlighting more expertise was required in "computer vision", "motion planning" and notably "mechanical design" pertaining to end-effectors [8]. Stagnating development of new designs for end-effectors has meant novel robotic solutions are under-capitalising on the potential improved capabilities brought by innovative end-effector design.

Current end-effector designs vary in both dimensions and grasping technologies. Various grasping technologies exist, common examples include motor actuated fingered grasping and vacuum induced suction grasping [9]. Accompanying these technologies has been a strong body of research applying algorithmic optimisation and selection techniques to both dimensions and select the most appropriate technology for a pre-defined application [10]. These methods have proved succesful when applied to specific tasks on a small sample of objects. However, they struggle to provide optimal solutions when presented with a variety of objects and multiple objectives.

Recent attempts to engineer new grasping technologies more suitable for general-purpose tasking, include compliant mechanisms and variable stiffness actuators for fingered grippers [15]. Although promising, these technologies have yet to prove their reliability in an industrial setting and are very much in their infancy. Conversely, little research has been undertaken to develop new end-effector designs that use a hybrid of existing grasping technologies. These existing grasping methods have already been validated by industry and have a long history of reliable use.

1.2 Research Challenge

This body of work looks to optimise the design of an end-effector to use a hybrid of fingered and suction grasping to achieve robust grasps. Both technologies are frequently recognised within industries as providing reliable performance and accuracy at a feasible cost. When teams at the first APC were asked, half of the 14 teams that did not use suction (fingered grasping only) said they would change their designs in the future to include suction [8]. Combining technologies can provide valuable synergies. Traditional fingered grasping methods provide the dexterity needed to grasp objects of varying geometrical complexity, whilst suction minimizes both translational and rotational degrees of freedom, making the grasp robust against wrenching forces.

The motivation is that the work conducted will help develop a new category of end-effector with improved capabilities through the technological synergies made and therefor outperform existing designs in general-purpose tasking.

1.3 Aims and Objectives

The aim of this work is to design an end-effector that is optimised to use both traditional fingered grasping and suction grasping, capable of robust grasping of a variety of objects.

In order to achieve the aim, three objectives are devised to guide the subsequent work:

- Objective 1 – Feature Identification and Design:
  Conduct a literature review of current designs and identify areas where synergies can be benefited from and subsequently design the new features in CAD software based on the prior identification.

- Objective 2 – Integration and Manufacture:
  Integrate all the designed features into one assembled prototype on CAD software and then manufacture the prototype end-effector.

- Objective 3 – Validate performance experimentally:
  Determine appropriate key performance metrics and validate the end-effectors performance experimentally by creating an idealised bin-picking scenario.

1.4 Project Structure

1.4.1 Project Timeline

The timeframe of this project spanned seven months, starting October 2019 and concluding end of April 2020. The project was arranged into three periods consisting of different categories of work required to successfully meet the aforementioned objectives by April 2020. A Gantt chart was used throughout the project to monitor progress and provide structure to research activities.

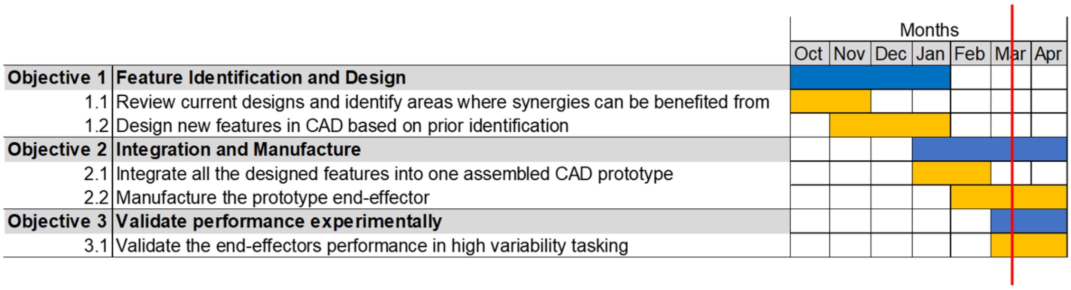


Figure 2: Summarised Gantt chart of project displaying progress till March 11th, 2020.

As a result of UCL's unforeseen closure on March 11th, 2020, all planned manufacturing and experimental activities past this date were suspended with immediate effect. Consequently, the sections of this report that are dependent on these activities have been modified or reduced to account for this.

1.4.2 Report Structure

The body of this report contains five sections which cover the course of action taken to achieve the outlined aim in section 1.3. An overview of each section can be found below along with a synopsis of the covered content:

- <u>Section 1 – Introduction:</u>
  The motivation and background of this project is discussed. Then the formulated aims and objectives are outlined, along with a brief structure of the project.
- <u>Section 2 – Literature Review on End-effector Designs:</u>
  A review of existing end-effector designs is conducted, first looking at how current grasping technologies work and their limitations. Then strengths and weakness of specific end-effector designs are evaluated. Finally, we investigate other works concerning grasping that might aid the design process.
- <u>Section 3 – End-effector Design Methodology:</u>
  In this section the design process is documented. First, design requirements for the end-effector are defined. Then the identification of key features to be designed are discussed and subsequently the final designs are presented. Lastly, the integration and manufacturing process undertaken to create the final end-effector prototype is detailed.
- <u>Section 4 – Experimentation and Discussion:</u>
  The experimentation method is outlined along with the key performance indicators chosen to measure the end-effectors performance. Additionally, a brief discussion regarding expected results is undertaken.
- <u>Section 5 – Conclusions:</u>
  The final section summarises the key findings and principles that can be extracted from this work, as well as suggest future work stemming from the limitations of the proposed design.

2 Literature review on end-effector designs

2.1 Overview

The field of robotic grasping relies on a strong foundation of kinematic, mechanics and mechanism theory. Research into novel robotic designs has only seen an active history over the last 50 years [16]. Cornerstone works such as the Stanford/JPL hand in 1987 [17] and Utah/MIT hand in 1984 [18] demonstrated robotic grasping's potential alongside creating a new benchmark for performance. The years since have seen a multitude of novel designs from industry and research. Nevertheless, these designs fundamental kinematics and mechanics principles remain the same. Consequently, in this section we seek to understand these principles through the lenses of current grasping technologies, notable end-effector designs and surrounding work concerning grasping.

2.2 Current Grasping Technologies

2.2.1 Fingered Grasping

Fundamental to grasping an object is providing sufficient force to sustain an objects weight such that it is in equilibrium, or equilibrium grasp. Fingered grasping uses two main approaches to achieve this: force closure and form closure [19]. These approaches are used in a variety of finger arrangements; this can range from simple two or three fingered grippers to anthropomorphic five fingered grippers.

Force closure seeks to create an equilibrium grasp by making the grasp resistant to perturbing forces or torques, also known as wrenches. This is achieved by applying sufficient reactional force in order to establish a frictional equilibrium between the object and the contact points of the finger [20].

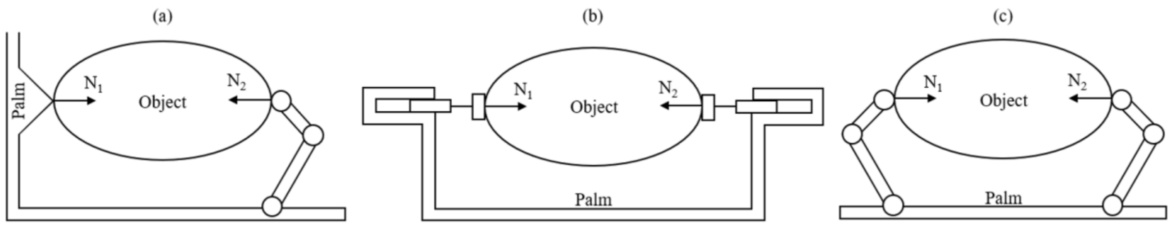


Figure 3: Illustrations of fingered graspers holding a rigid ellipse object where N denotes the reaction force. (a) Fingered grasp between one finger and the palm of the gripper. (b) Two-fingered parallel grasp. (c) Two-fingered grasp.

In Figure 3 three basic examples of fingered force closure are illustrated. Using the Coulomb Friction Point Contact Model, we can calculate the total necessary reaction force to create a frictional equilibrium to be μ/ma. Where μ is the coefficient of friction between the two contact surfaces, m is the mass of the object and a is the object's acceleration. Assuming the force is equally distributed amongst n number of contacts and g the acceleration due to gravity is considered, we can calculate the total force required to grasp the object F, to be:

$$F = \frac{m(a+g)}{\mu n}$$

Form closure achieves an equilibrium grasp by moving parts of the finger mechanism around the object. Once the mechanism is immobilised the fingers act as a rigid structure creating a secure grasp around the object [21]. We look at form closure further in section 2.2.3, which can be used in isolation to produce another method of grasping. Form and force closure are often used in duality in fingered grasps, compensating for each other when slippage occurs.

2.2.2 Suction Grasping

Suction grasping employs the adhering force generated by the negative fluid pressure of air to grasp objects. To do this a suction cup is connected to a partial vacuum. Figure 4 demonstrates how this works, the partial vacuum created within the suction cup creates a pressure difference. As a result, the higher atmospheric pressure exerts a force on the surface covered by the cup thereby grasping the object. Assuming the suction cups form a perfect seal and force is applied perpendicularly to the surface of the object. If P_{atm} is the atmospheric pressure, P_{vac} is the vacuum pressure and r is internal radius of the suction cup in contact with the object, we can calculate force produced by a single cup to be:

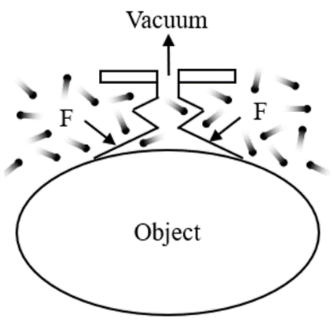


Figure 4: Illustration of suction grasping. A bellow suction cup is connected to a vacuum. Dots represent gas molecules exerting pressure on the surface of the suction cup.

$$F = \pi r^2(P_{atm} - P_{vac})$$

Multiple suction cups are often used on end-effector designs thereby multiplying the grasping force. Suction cups are often bellow shaped, as seen in Figure 4, and built from an elastic or flexible material in order to adapt to the object's contours and form a tight seal [22]. In many cases assuming a perfect seal is often too simplistic. Often the suction cup cannot fully adhere to geometrically complex surfaces thereby creating a weak seal and reduces the cups ability to generate force. Moreover, porous objects prevent seals from forming. As a result, suction alone can sometimes be inadequate. Work to optimise the best location to position a suction cup to achieve a high-quality seal such as the use of convolutional neural networks [23] provides promise but requires extensive datasets of similar objects beforehand.

2.2.3 Form Grasping

Form graspers, as described in section 2.1.1, are inspired by form closures commonly seen in fingered end-effectors. These graspers employ a singular mass filled with a fluid and rigid granules or skeleton structure. These masses envelope the object and then evacuate the internal fluid, leaving the rigid internals wrapped around the object, forming a secure grasp.

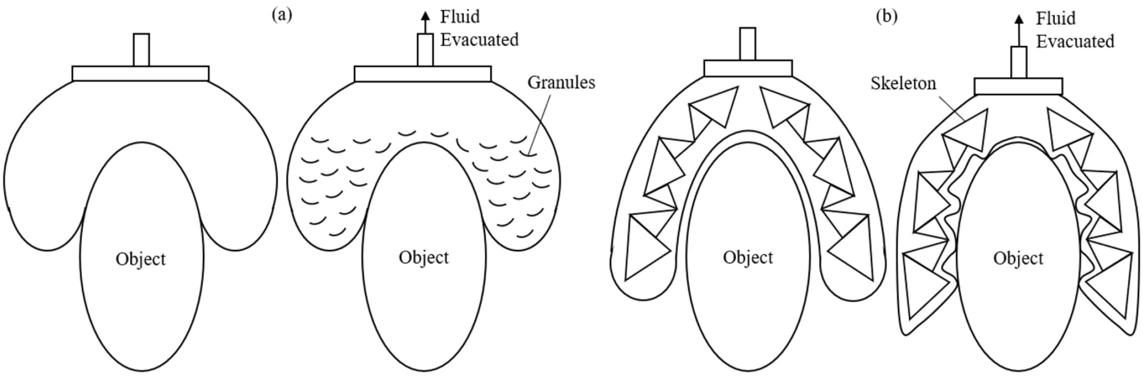


Figure 5: Illustration of form grasping. (a) Granular jamming grasper. (b) Internal skeleton grasper.

Figure 5(a) demonstrates this concept by referencing the Universal Robotic Gripper [24] which uses a balloon filled with coffee granules to create a rigid structure around the object. Figure 5(b) demonstrates the Origami Gripper [25] which uses a silicone-rubber skeleton structure inside a balloon to achieve a similar effect. Form grasping designs are simple, reliable and have demonstrated an ability to pick up a wide range of objects given there is a protruding edge. However, when challenged with a flat or acutely curved surface these designs fail to create a secure grasp.

2.3 NOTABLE END-EFFECTOR DESIGNS

2.3.1 Designs from Academia

Cartman's Multi-Modal End-effector

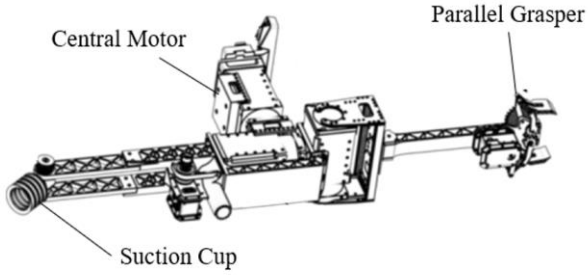


Figure 6: Drawing of the multi-modal end-effector used on 'Cartman', the 2017 APC winner [27].

'Cartman' was the winning submissions in the 2017 Amazon Picking Challenge. The end-effector used had two ends, one equipped with a suction cup and the other with a parallel grasper [26]. A central servo motor then spun the end-effector ends depending on the mode of grasping chosen by the planning algorithm as seen in Figure 6.

Advantages: Use of both suction and fingered grasping allowed the end-effector to change grasping approach depending on the object being grasped. This proved effective at grasping a variety of objects in comparison to its rivals in the 2017 APC, contributing to 'Cartman's' win.

Disadvantages: The central servo motor meant the design had to frequently switch between grasping modes making the grasping process slow. Moreover, both grasping technologies were used separately meaning the mechanical synergies produced by concurrent use were not explored.

RBO Hand 2

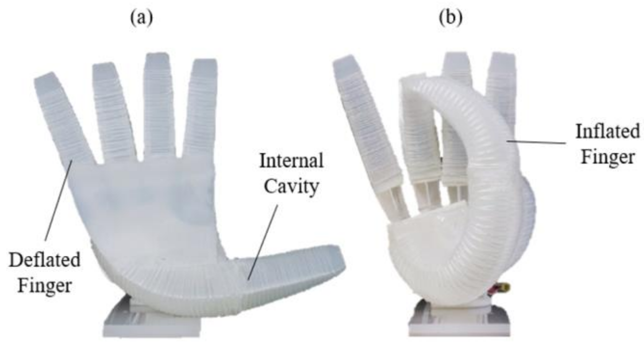


Figure 7: RBO Hand 2 [28]. (a) Completely deflated hand. (b) Inflated thumb and ring finger touching.

The RBO Hand 2 uses pneumatic actuation to achieve underactuated fingered grasping. Underactuated grasping occurs when the system has fewer actuators than degrees of freedom. This is done using an internal cavity in each finger. When these cavities are inflated with air the finger then curls as in Figure 7(b) allowing the hand to grasp objects [27].

Advantages: The underactuated design allows the fingers adapt to contours of the object and thereby follow complex trajectories which are otherwise difficult to plan.

Disadvantages: Although an underactuated design allows for complex grasps it also inhibits precise control over the movement of the hands. This means the fingers are unable to follow specific grasping policies that may involve coordinated movement of each finger.

2.3.2 Commercially Available Designs

Shadow Dexterous Hand

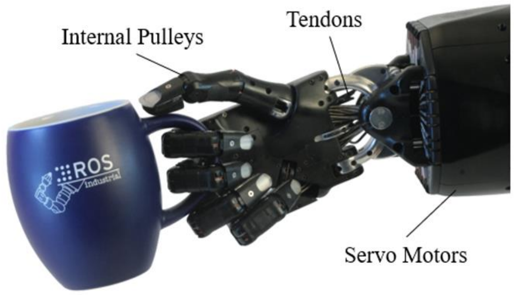


Figure 8: Shadow Dexterous Hand by the Shadow Robotics Company [29].

The Shadow Dexterous Hand is often considered one of the most advanced anthropomorphic end-effector designs. The design provides 20 degrees of freedom and therefore precise positional control. This is achieved through a compactly designed tendon and pulley system, where tendons are driven by a servo motor embedded into the forearm of the device [28].

Advantages: The high degree of freedom design allows precise control over the pose of the end-effector resulting in intricate grasps and high overall dexterity. Moreover, the design's dimensions closely match that of the human hand thereby optimising the design for grasping of objects commonly handled by human hands.

Disadvantages: To achieve high dexterity in a compact form factor this design concedes its robustness by using delicate finger mechanisms and actuation system. Moreover, the parts used make the design costly to produce, often limiting usage to well-funded research projects.

Robotiq 3-Finger Gripper

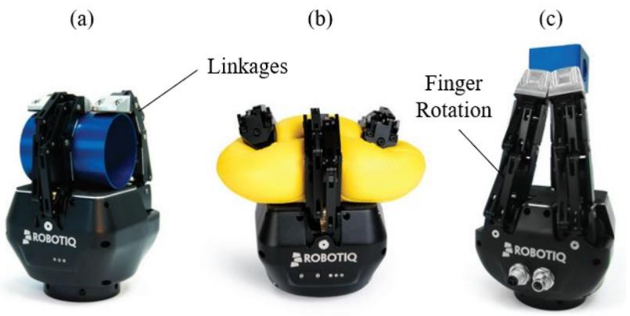


Figure 9: Robotiq 3-Finger Gripper [30]. (a) Basic grasp. (b) Wide grasp. (c) Pinch grasp.

Robotiq's 3-Fingered gripper is a robust fingered end-effector targeted for industrial use. The gripper provides three grasping methods which are shown in Figure 9. The range of grasps achieved are attributed to the two adjacent fingers being able to rotate 16 degrees either direction in the vertical plane [29].

Advantages: The linkages provide long-lasting finger actuation which are unlike tendons which can become slack over time. Moreover, the unique finger rotation mechanism makes this design able to grasp larger objects as well as precisely grasp smaller objects.

Disadvantages: The parallel arrangement of fingers means the gripper struggles with spherical objects like a tennis ball. Furthermore, the linkage system used although robust does not produce a smooth motion as the fingers close resulting in sub-optimal grasps when objects with protruding edges like a cube are grasped.

2.3.3 Existing Hybrid Designs

iGRIPP 4

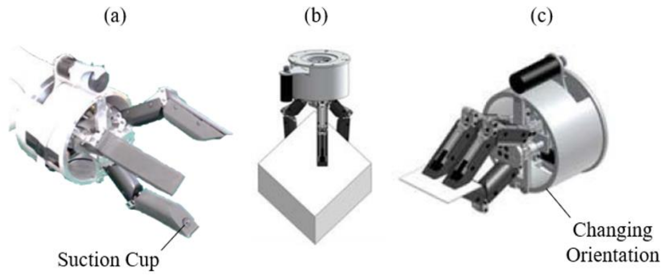


Figure 10: iGRIPP4 End-effector [31]. (a) iGRIPP 4 in partial grasp. (b) Illustration of grasping a cube with suction cups. (c) Illustration of precise grasping of a sheet with both suction and grasping.

The iGRIPP 4 was conceived in 2013 and is one of the first end-effectors to use both suction and fingered grasping concurrently. The design embeds suction cups in the fingertips of the grasper as seen in Figure 10(a) [30]. Additionally, a secondary motor to vary the orientation of the fingers is integrated into the designs palm.

Advantages: The design can execute a unique set of grasps as seen in Figure 10(b) where a cube is grasped on its faces using suction cups as well as rotate to differing positions as seen in Figure 10(c). This extra functionality stems from its hybrid grasping approach.

Disadvantages: The fingers used have only two phalanges and use internal linkages, as a result the finger's grasping motion is not smooth and grasping of larger objects is less feasible. Only placement of suction cups on the tips of the fingers was explored and therefore the design did not seek to use form closure and suction concurrently.

RightHand Robotics GripperV5

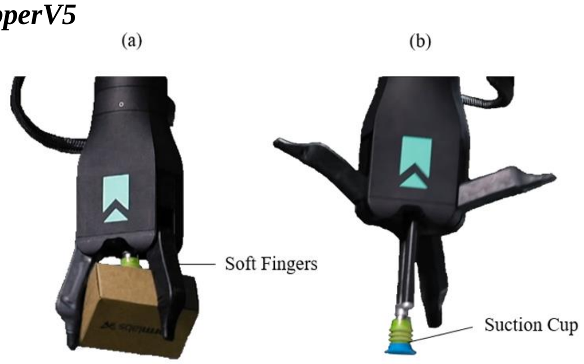


Figure 11: RightHand Robotics GripperV5 uses a suction cup embedded in the palm that can extend to grasp the object and soft fingers to envelope it [32]. (a) Grasp of small box using soft fingers. (b) Extended suction cup.

The RightHand Robotics GripperV5 uses three fingered grasping and a suction cup within the palm of the end-effector as seen in Figure 11. In practise the suction cup extends from the palm toward the object and creates a seal with the objects surface. The suction cup along with the now grasped object is then retracted to the position seen in Figure 11 and the soft fingers than wrap around the object [36].

Advantages: The uses of suction as the main method of grasping and fingers to stabilise the object after it has been grasped by the suction cup produces a fast grasp and secure grasp. Moreover, the soft fingers mean the fingers deform around the object providing form closure.

Disadvantages: The device has only one suction cup and fixed fingers that have a single phalange with one degree of freedom. This means the grasping motion is simplistic and therefore the end-effector struggles to grasp prismatic and cylindrical shaped objects.

2.4 SURROUNDING WORK CONCERNING GRASPING

2.4.1 Grasping Taxonomies

Work concerning the training of grasp planning algorithms has given rise to research regarding grasping taxonomies. These taxonomies provide a comparative view between different grasps and their execution. Leading this research has been the analysis of 'everyday grasps', which look at human hands grasping objects that are typically used throughout an individual's day. J. Liu et al. followed two individual's typical days and took pictures of all grasps executed [32]. These pictures were then classified by their perceived motion, force, and stiffness. G. Rogez et al. went further and feed a neural network over 12,000 RGB-D images of 71 different grasps [38]. The resulting algorithm can analyse unseen photos and perform force and contact point prediction. As a result, these taxonomies can be referenced when designing an end-effector and help predict the efficacy of a prototype.

2.4.2 Amazon Picking Challenge Analysis

A key work already referenced throughout this review is the analysis of the 2017 Amazon Picking Challenge. Challenges like the APC are very successful at fostering innovate solutions to standard problems. The 2017 APC reflected this with 16 different entries all with distinct approaches. N. Cornell et al. performed a post-competition analysis of these in order to identify promising approaches and areas of improvement [8]. On the analysis of objects grasped it was found that a sparkplug, wire mesh pencil holder and netted dog toy proved to be the most challenging to grasp. Additionally, the analysis demonstrated the need for grasps to be mindful not to damage the object being grasped. Books were an example of this, where grabbing the spine or cover could cause the book to dangle and get damaged. These areas of improvement amongst others mentioned in the analysis can be used when designing for improved capability in an end-effector.

2.5 SUMMARY

The review determined the underpinnings of current grasping technologies, strengths and weaknesses of notable end-effector designs and key surrounding work concerning grasping to reference throughout the end-effectors design:

- Grasping Technologies:
  The quality of a fingered grasp is dependent on the finger mechanism and actuation system used to achieve force and form closure. Moreover, suction grasping relies on quality seals being formed with the object's surface to prove effective. Additional grasping technologies such as form grasping can provide further understanding of the mechanics of a secure grasp.

- Notable End-effector Designs:
  Stronger end-effector designed opted for three-phalanges fingers and a compactly designed finger mechanism and actuation system. The most innovative design also opted to use some form of finger orientation mechanism. Furthermore, the most common drawback amongst designs was identified as a lack of fingertip or distal for precision pinch grasps

- Surrounding Work Concerning Grasping:
  Grasping taxonomies and analysis of the 2017 Amazon Picking Challenge act as useful texts to reference throughout the design process, highlighting the novelties of human grasps and flaws of current end-effector designs.

3 END-EFFECTOR DESIGN METHODOLOGY

3.1 REQUIREMENTS AND DESIGN PROCESS

3.1.1 Function and Design Process

Leading from the findings summarised in section 2.5, the end-effector design is expected to securely grasp a wide variety of objects from cluttered environments akin to general-purpose tasking such as bin-picking. As a result, the design must accommodate for the difficulties associated with grasping objects of varying material properties and geometrical complexity. To achieve this, a methodical design process was followed as outlined in Figure 12:

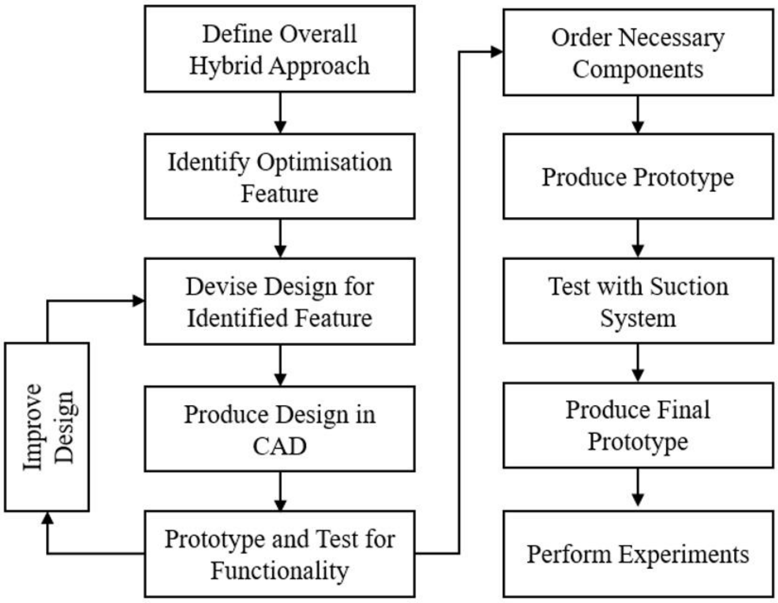


Figure 12: Flowchart of the design process used throughout the project.

3.1.2 Design Constraints

Minimum Payload

To succeed at securely grasping a variety of objects the end-effector must be able to withstand a minimum payload; however, exceeding this minimum is not necessarily advantageous. A cursory survey of the maximum weights of commonly grasped objects was conducted to help determine an approximate minimum payload. Using the best-selling goods on Amazon.co.uk [34] and the common household goods from the Office for National Statistics [35], a median upper limit of 1kg was determined. As a result, the design was expected to grasp a minimum payload of 1.5kg and thereby provide a sufficient safety factor.

End-effector Length

A constraint closely related to stroke size is the length of the end-effector from the base of the palm to end of the finger. This length determines the range of geometries the end-effector is able to grasp. Objects grasped in general-purpose tasks such as bin-picking are often designed to be grasped by human hands. As a result, the end-effector’s length must be similar to that of the human hand. A study of proportions of the human body by the National Aeronautics and Space Administration (NASA) found that on average male hands ranged in length from 179mm to 206mm from the base of the palm to end of the finger [36]. Therefore, it was necessary the length of end-effector from the base of the palm to end of the finger fell within this range.

3.2 FEATURE IDENTIFICATION AND DESIGN

Aligned with the aim in section 1.3, the proposed design seeks to use force and form closure from fingered grasping (see section 2.2.1) and simultaneously use the principles of suction grasping (see section 2.2.2). In order to do so, a preliminary decision regarding the placement of suction cups on a fingered end-effector was required. Existing hybrid designs reviewed in section 2.3.3 had suction cups located on the fingertips and palm of the end-effector. However, as critiqued, this meant either form or force closure was not used when grasping an object.

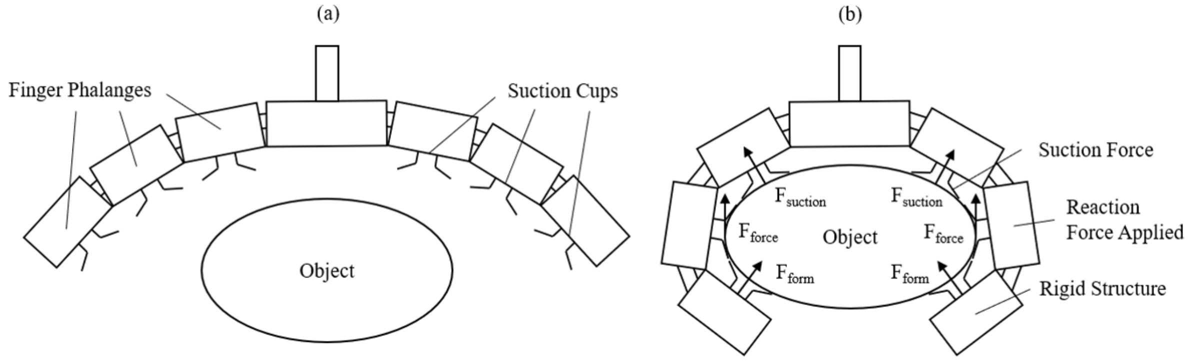


Figure 13: Illustration of two fingered end-effector with multiple suction cups on the inner side of each finger. (a) Open grasp. (b) Closed grasp. $F_{suction}$ denotes the force generated by the vacuum within the cups (suction force). F_{force} denotes the frictional force generated by the reaction force applied normal to the contact point of the finger (force closure). F_{form} denotes the force generated by the rigid flange supporting the object (form closure).

Placement of multiple suction cups on the inner side of a finger allows for all grasping methods to be used at once. Figure 13(b) demonstrates this concept, the negative fluid pressure of air generated by the suction cups exerts a force that pulls the object into the phalanges of the finger. As the finger mechanism actuates, the flanges exert a reaction force normal to the contact point which is then compounded by the aforementioned suction force. This results in a large reaction force at the contact points with the object and as a result generates a greater frictional force, preventing the object from slipping out of the grasp. Finally, once the finger mechanism is immobilised it acts as a rigid supporting structure around the object.

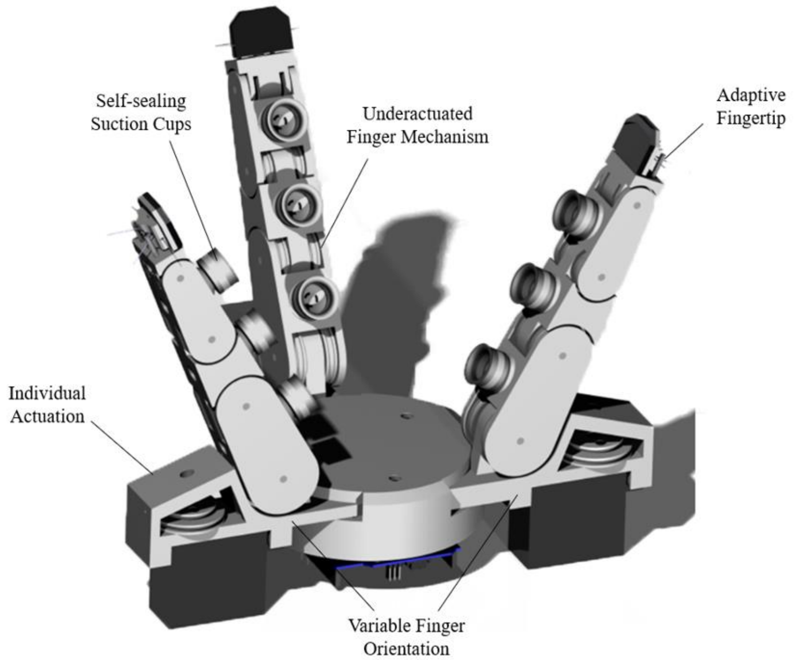


Figure 14: Overall design and summary of the features identified to optimise grasping performance.

With this preliminary decision made a subsequent optimisation process was undertaken. This involved the identification of key features of an end-effector's design that could maximise the mechanical benefits of using suction and fingered grasping concurrently. The overall design can be seen in Figure 14 with the various features that were identified. Ultimately, the design opted for an individual actuated three fingered approach with self-sealing suctions cups on the inside of each phalange. Adaptive fingertips were used to provide precision grasping, whilst a mechanism was designed into the palm that provided a wider range of grasps by varying the orientation of two of the fingers.

3.2.1 Underactuated Finger Mechanism

To decide on an appropriate finger mechanism, an assessment of various types of finger mechanisms was carried out as seen in Table 1. An important consideration was the need to integrate a pneumatic system for the suction cups into each finger. As a result, the compactness of the design was a key constraint.

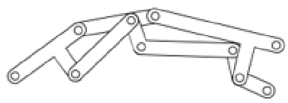
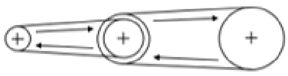
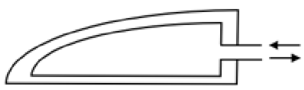
Mechanism	Description	Advantages	Disadvantages
Linkages 	Rigid links are fastened together, input force translated through links providing finger movement.	• Very robust mechanism, long lifetime usage. • Tolerates high grasping force.	• Large form factor and bulks finger size. • Movement not smooth.
Geared 	Rotation of an input gear rotates a series of gears in a train formation causing finger movement.	• Compact system. • Easy to calibrate actuation trajectory and speed using gearing ratios.	• High DOF requires multiple motors. • Gearing prone to jamming, lower lifetime usage.
Belt and Pulley 	A system of driving belts and free/fixed pulleys are used to translate motion along the finger.	• Pulleys provide continuous smooth motion. • Transfers high grasping force.	• Belts can slack over time. • Large form factor uses entirety of internal finger.
Tendon 	Taught string is pulled at one end causing constriction and thereby contracting the finger.	• Most compact system designs. • High tensile tendons transfer high force.	• Requires guides to prevent loss of tension in tendon. • Needs secondary restoring force.
Pneumatic/Hydraulic 	A working fluid is forced into an internal cavity, causing the pressure difference to curl the finger.	• Executes highly compliant grasps around objects. • Very inexpensive and simple design.	• Uses entirety of internal finger space. • Prone to working fluid leakage.

Table 1: Comparison of common finger mechanisms. DOF refers to Degree of Freedom.

The final mechanism chosen used a combination of tendons and pulleys, this is detailed in Figure 15. This allowed for the placement of three suction cups along each phalange and three degrees-of-freedom, therefore providing a compact solution with a wide range of motion. Moreover, the resulting design is also underactuated, meaning more degrees of freedom than actuators, which allows the finger to comply to the surface geometries of the object. This is optimal for allowing the suction cups to naturally position themselves on the object with a high-quality seal.

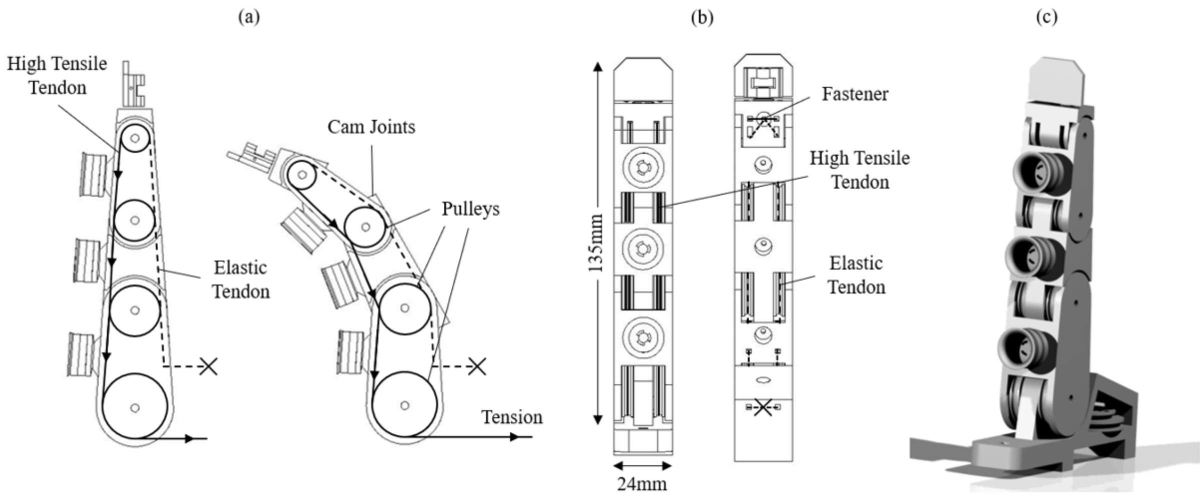


Figure 15: Tendon and pulley finger mechanism used in the final design. (a) Illustration of finger contraction from a side view. (b) Illustration of front and back view of finger mechanism. (c) CAD render of finger mechanism.

The mechanism employs the use of two types of tendons, high tensile tendons and elastic tendons. Two high tensile tendons run along the inner side of the finger and act to contract the finger. This can be seen in Figure 15(a) where a tension is applied to the tendon causing a moment around each joint of the finger resulting in its contraction. Additionally, each high tensile tendon is run around a series of three pulleys as seen in Figure 15(b). This helps guide the tendons path resulting in a smooth and reliable contracting motion.

To provide a restoring force, two elastic tendons run along the back side of the finger as seen in Figure 15(a), these tendons are secured to the base of finger as denoted by an ‘X’ in Figure 15. The tendons elastic nature means they extend when a moment is applied around each joint. Once the moment is removed the extension, as per Hooke’s law, causes a restoring force which reverts the finger back to its original position.

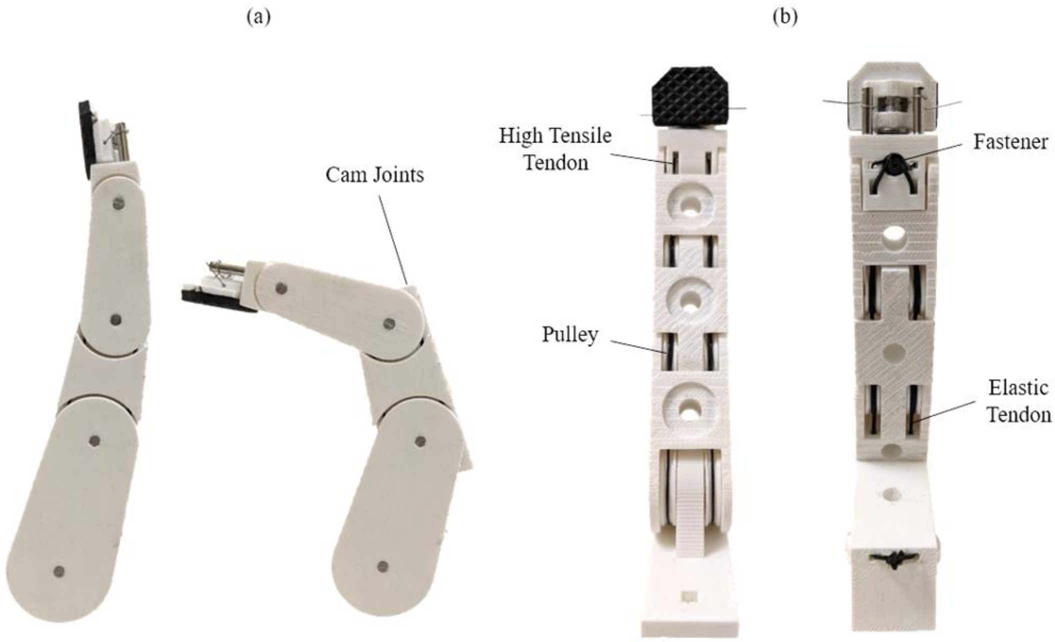


Figure 16: Manufactured finger mechanism used in the final design. (a) Open finger and contracted finger. (b) Front and back view of finger mechanism.

A manufactured finger is shown in Figure 16, 0.70mm diameter badminton chord is used for the high tensile tendons and 1.5mm diameter bungee cord is used for the elastic tendons.

3.2.2 Individual Actuation

Key to operating the finger mechanism was devising an appropriate actuation system to apply tension to the tendons. End-effectors are frequently grouped into two categories: individually actuated fingers and simultaneously actuated fingers. Simultaneously actuation allows the use of a single actuator to contract all fingers in unison. Individual actuation often employs the use of multiple actuators, often one for each finger, allowing for more complex grasping strategies. The decision to use either approach is often dictated by the complexity of the end-effector's application, simpler applications often opt for simultaneous actuation as it reduces design complexity and cost.

The ability for suction to reduce both translational and rotational degrees of freedom means a single finger can eliminate the wrenching forces of the grasped object. This allows for the remaining fingers to use force and form closure to completely secure the grasp. This is demonstrated on a book in Figure 17 which prevents the spine or cover from dangling and getting damaged, a common occurrence noted in the 2017 APC.

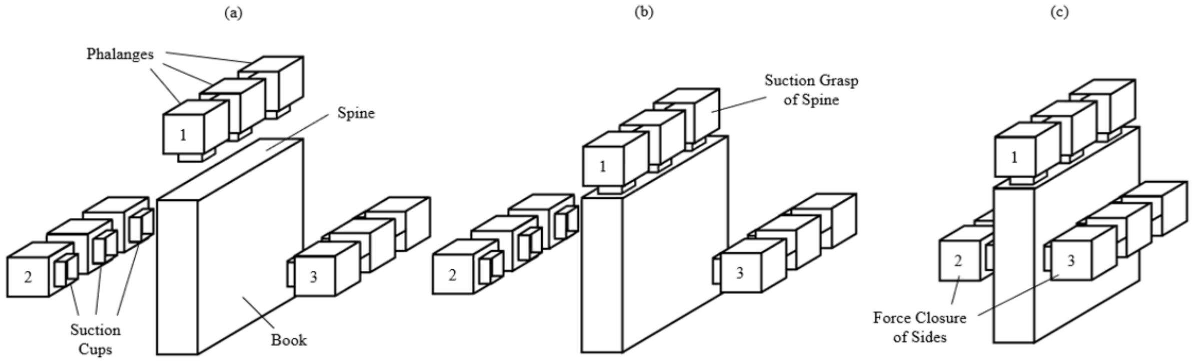


Figure 17: Individually actuated fingers (1, 2, 3) with suction cups grasping a book. (a) All three fingers positioned around book. (b) Finger 1 grasps the spine of the book using suction which immobilises it. (c) Fingers 2 and 3 grasp the sides of the book using force closure to complete a secure grasp of the book.

As a result of the novel grasping strategies that could be achieved, such as the one demonstrated in Figure 17, the design opted for individual actuation thereby maximising the variety of objects that could be grasped. The choice of actuator had to allow for precise control and high holding force when powered off. Servo motors were chosen for these reasons and could be precisely controlled from an Arduino Uno using pulse width modulation. A setup of the actuation mechanism used at the base of each finger is detailed in Figure 18.

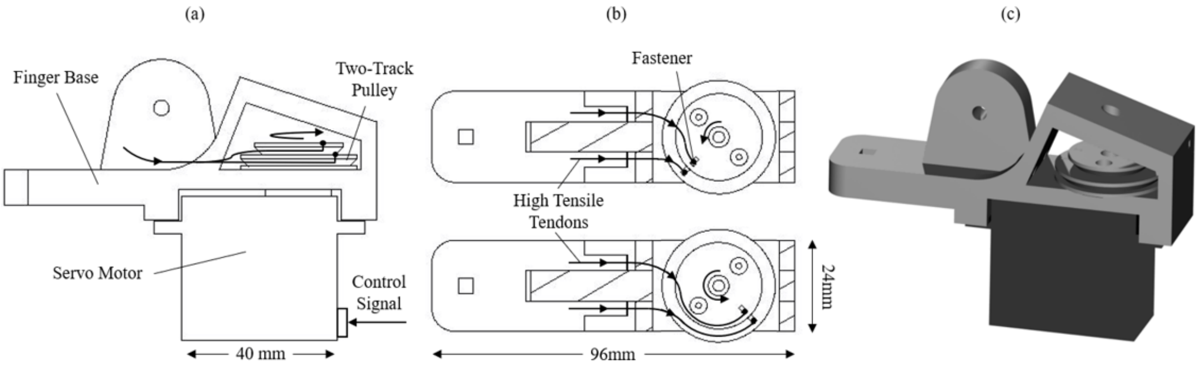


Figure 18: Actuation system used to apply tension to high tensile tendons. (a) Illustration of actuation system from a side view. (b) Illustration of two-track pulley system from a top-down cross-sectional view. (c) CAD render of actuation system used.

In Figure 18(a) the high tensile tendons can be seen running into the two-track pulley which guides either tendon to the top or bottom of the track of the pulley. These tendons are fastened to the pulley such that when the servo motor is operated, a tangential force applies tension to the tendons. Figure 18(b) demonstrates this when no object is in the finger's grasp and therefore more tendon is thread into the pulley as the servo motor rotates. A fabricated actuation system is shown in Figure 19 which is replicated at the base of each finger.

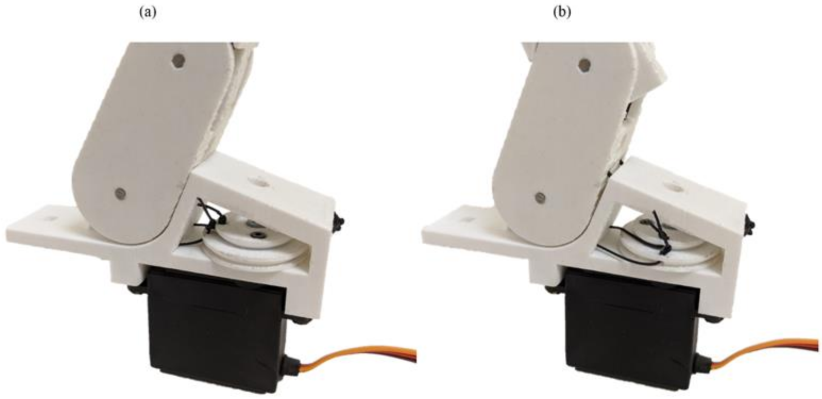


Figure 19: Fabricated actuation system (a) Idle position. (b) Actuated position.

3.2.3 Self-Sealing Suction Cups

The choice of suction cup is the most important factor in determining the performance of a suction grasping end-effector. Convention has been to use simple 'below' shaped cups like that used in the 'Cartman' multi-modal end-effector in section 2.3.1. These designs provide flex and compliance around the objects surface, thereby providing tight seals. However, when multiple cups are used not all cups form seals with the object resulting in pressure losses and therefore a weak grasp. Solutions such as pressure-saving valves and regulators can be used to counter this but are often bulky and expensive. Instead, a novel self-sealing suction cup design is proposed that prevents pressure loss by sealing the cup until it is in contact with an object. This design is largely based on work conducted by C. Kessens et al. in 2010 [37] and 2016 [38] on self-sealing suction cup arrays.

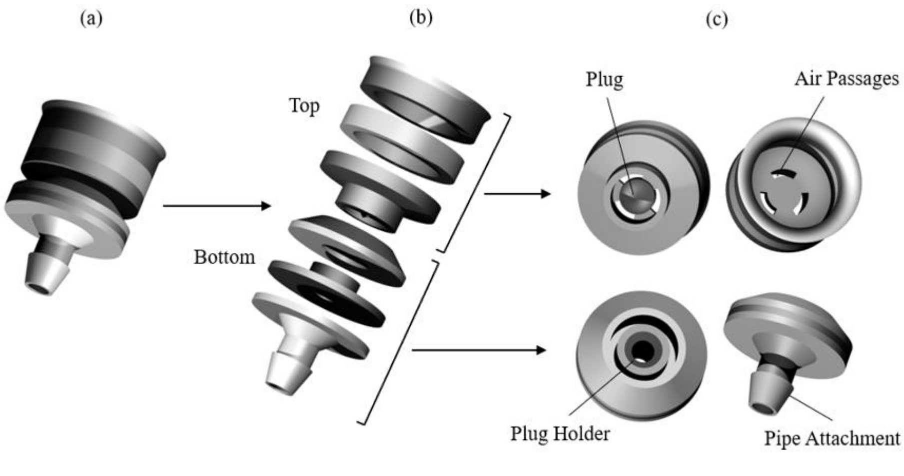


Figure 20: Self-sealing suction cup design. (a) Assembled self-sealing suction cup. (b) Exploded view of the cup's layered structure. (c) Key features designed into the top and bottom portions of the cup.

The design capitalises on the nature of force closure exerting a normal force on the lips of the suction cup and thereby compressing them. The compression actuates a small internal plug which exposes the object to the partial vacuum connected to the cups. This is achieved by fabricating the suction cup from layers of flexible rubber and rigid plastic material. Figure 21 provides a schematic and overview of each layer's material properties.

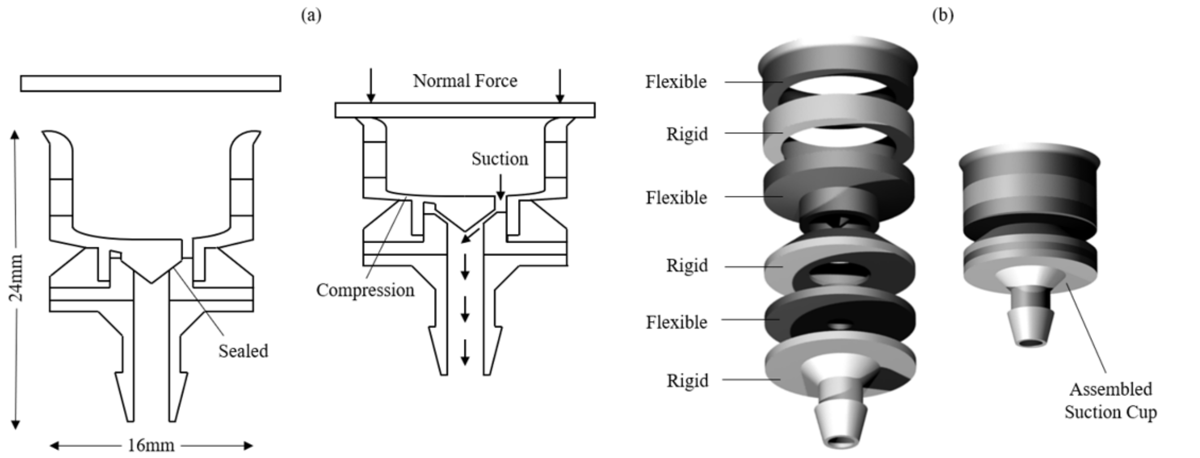


Figure 21: Summary of the suction cup's self-sealing process. (a) Schematic of compressed and uncompressed suction cup. (b) Material properties of each layer of the suction cup.

As the cup comes into contact with the surface the top compresses raising the plug slightly. This provides an opening for the vacuum to evacuate the inside of the suction cup thereby creating a tight seal, as seen in Figure 21(a). This is made possible by the rigid ring shown in Figure 21(b), directly underneath the lip of the cup which allows normal force to be translated down to the plug.

Figure 22: Early version of self-sealing suction cup. (a) Side view. (b) Front view showing TangoBlackPlus and VeroWhite material used to create flexible and rigid layers.

The suction cup was fabricated using an Objet Connex500 3D multi-material printer. The flexible material used was TangoBlackPlus and the rigid material was VeroWhite. An early prototype can be seen in Figure 22.

3.2.4 Adaptive Fingertips

A feature often overlooked in end-effector design is the tip or distal. Commonly this part of the end-effector is either static or ignored to reduce the design's complexity. Human hands utilise both the fat and bone structure of the fingertip and minor rotations of the finger to achieve high precision pinches. This allows the grasping of items with highly contoured surfaces. An example of such an object can be found in the 2017 APC, where the majority of end-effectors failed to grasp sparkplugs due to its small form and highly contoured surface.

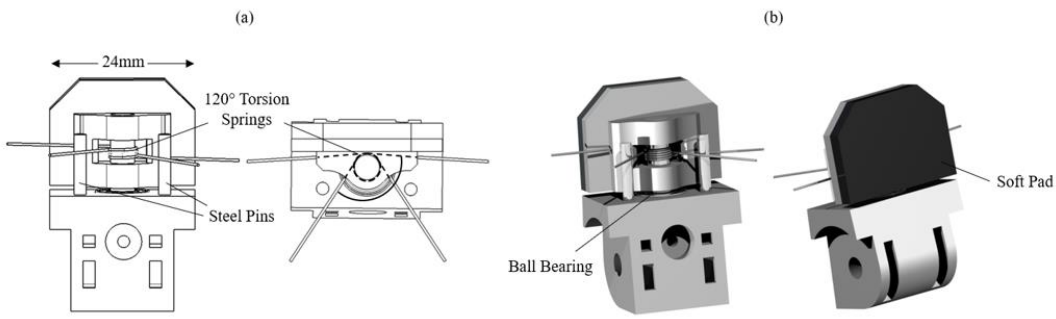


Figure 23: Adaptive fingertip design. (a) Schematic of fingertips. (b) CAD render of fingertip.

Consequently, the design aimed to mimic the mechanics of the human finger using a sprung tip to allow minor rotation and a soft material adhered to the rigid fingertip to mimic the fat and bone structure of the human finger. The resulting design can be seen in Figure 23.

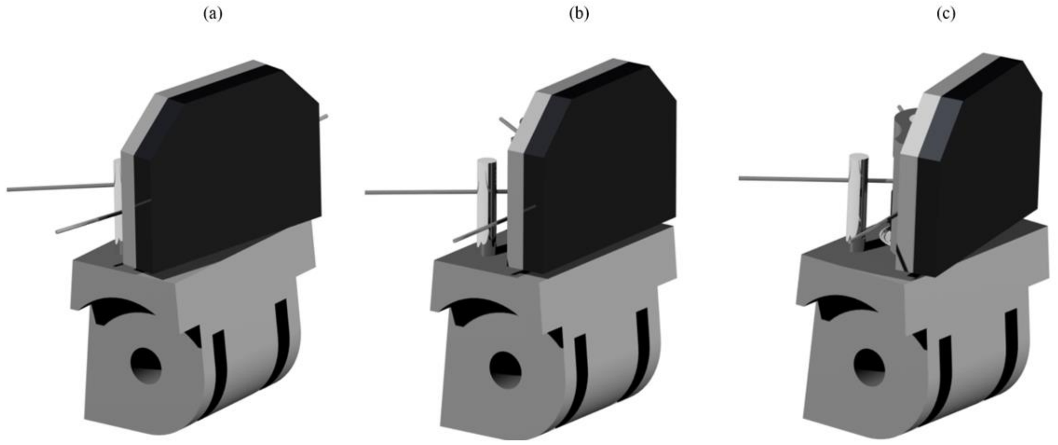


Figure 24: Finger rotation. (a) Clockwise rotation. (b) Idle position. (c) Anticlockwise rotation.

The rotation clockwise and anticlockwise as seen in Figure 24 is aided by the axle being grounded in a ball bearing. When the tip is pressed against a surface the normal force overcomes the stiffness of the torsion spring and the tip begins to rotate. Once released the compression of the torsion spring against the steel pins restores the tip to its idle position seen in Figure 24(b). A fabrication of the adaptive fingertip can be seen in Figure 25.

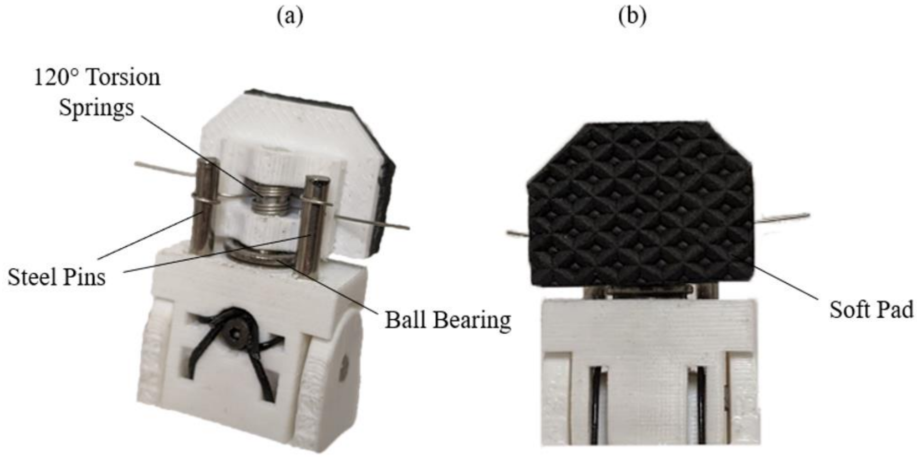


Figure 25: Fabricated adaptive fingertip. (a) Back view. (b) Front view.

3.2.5 Variable Finger Orientation

The number and orientation of fingers dictates the shapes of objects an end-effector is able to grasp. Two fingered parallel graspers are often seen in the simplest of applications, providing force closure grasping on flat surface but struggle on more geometrically complex objects. More advanced designs range from three fingers to anthropomorphic five fingered designs. Although more fingers might seem advantageous, often they add unwanted complexity and size to the end-effector.

Instead, three fingered designs have proven to be effective at grasping an ample number of objects without adding unnecessary complexity. A common pose chosen is a 120-degree separation of all fingers, this is optimal for grasping spherical objects but is less effective at grasping more cubic objects. Therefore, a mechanism is designed into the palm of the end-effector that orients three fingers to two distinct poses depending on which is optimal for the object being grasped, as seen in Figure 26. The design is based on work proposed by M. Luo et al. on finger orientation [39].

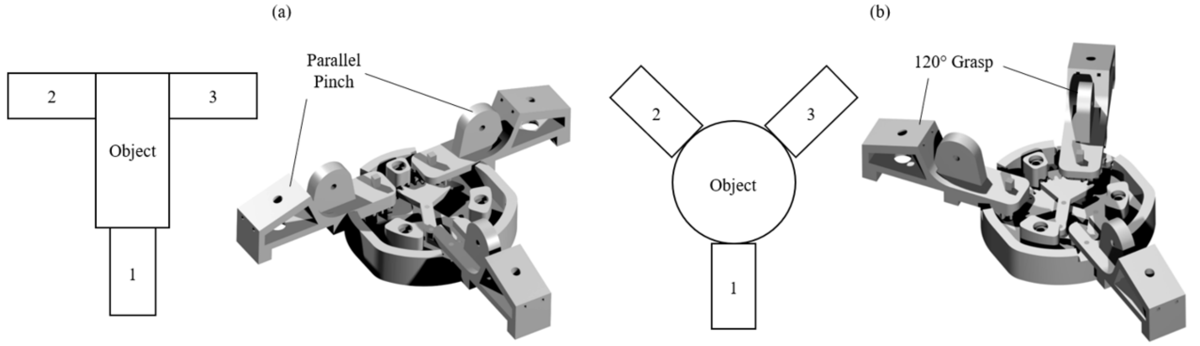


Figure 26: Three fingered arrangement in two poses. (a) Schematic and setup of the three fingers (1, 2 ,3) grasping a rectangular object. (b) Schematic and setup of the three fingers (1, 2 ,3) grasping a spherical object.

The design is achieved using a two-level planetary gear mechanism embedded into the palm of the end-effector. This mechanism is driven by a linear motion beneath the end-effector, the motion is translated through the linkage structure to a rotational motion that rotates and moves the planet gear. These gears are secured to the fingers using a square axle allowing the transition between possess, this is closely examined in Figure 27.

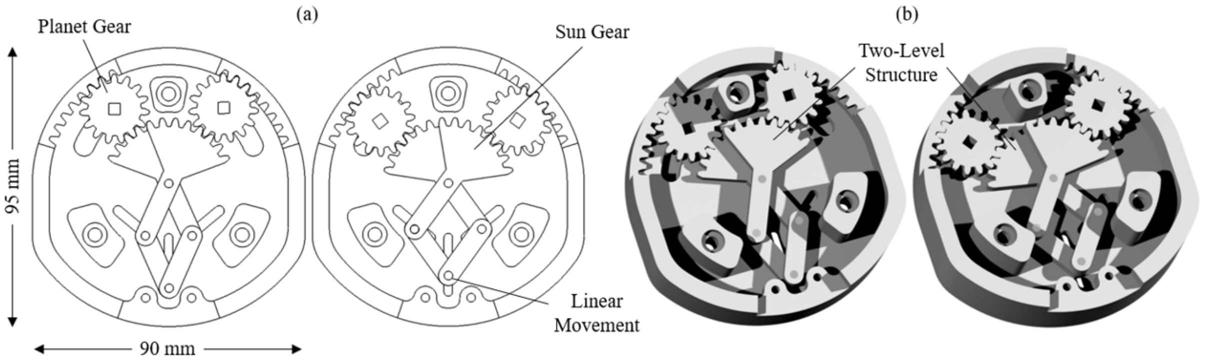


Figure 27: Variable finger orientation mechanism. (a) Schematic of planetary gear mechanism used to achieve planet gear rotation. (b) CAD rendering of the mechanism highlighting two-level structure.

The mechanism was modelled in Linkage, a mechanism simulation software [40], to select an appropriate gearing ratio. Once a ratio was chosen R. Hessmer's gear dimensioning software [41] was used to create the designs of both the sun, planet and ring gear. Finally, the gearing design was integrated into a two-level mechanism in palm of the end-effector. A fabrication of the mechanism can be seen in Figure 28.

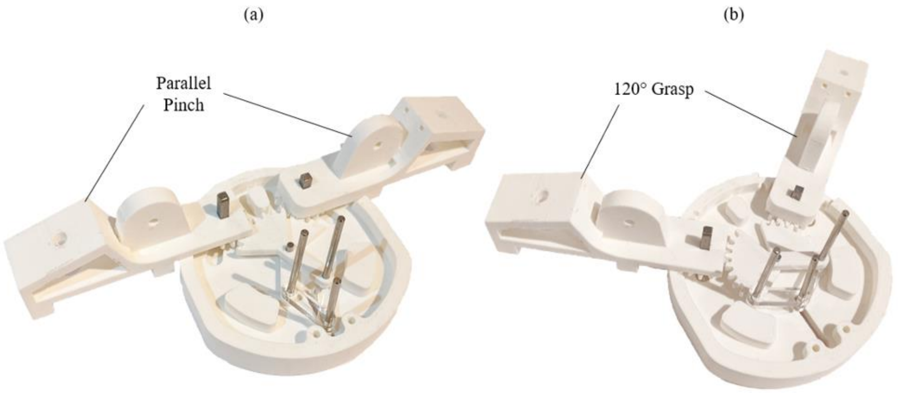


Figure 28: Fabricated variable finger orientation mechanism. (a) Parallel pinch pose. (b) 120° grasping pose.

3.3 INTEGRATION AND MANUFACTURE

3.3.1 Assembled CAD Prototype

Once all features were identified and designed an integration process aligned with Objective 2 was undertaken. The aforementioned features were revised to achieve this, and a mounting for the Arduino Uno microcontroller was designed beneath the palm. The final design of the end-effector can be seen in Figure 29.

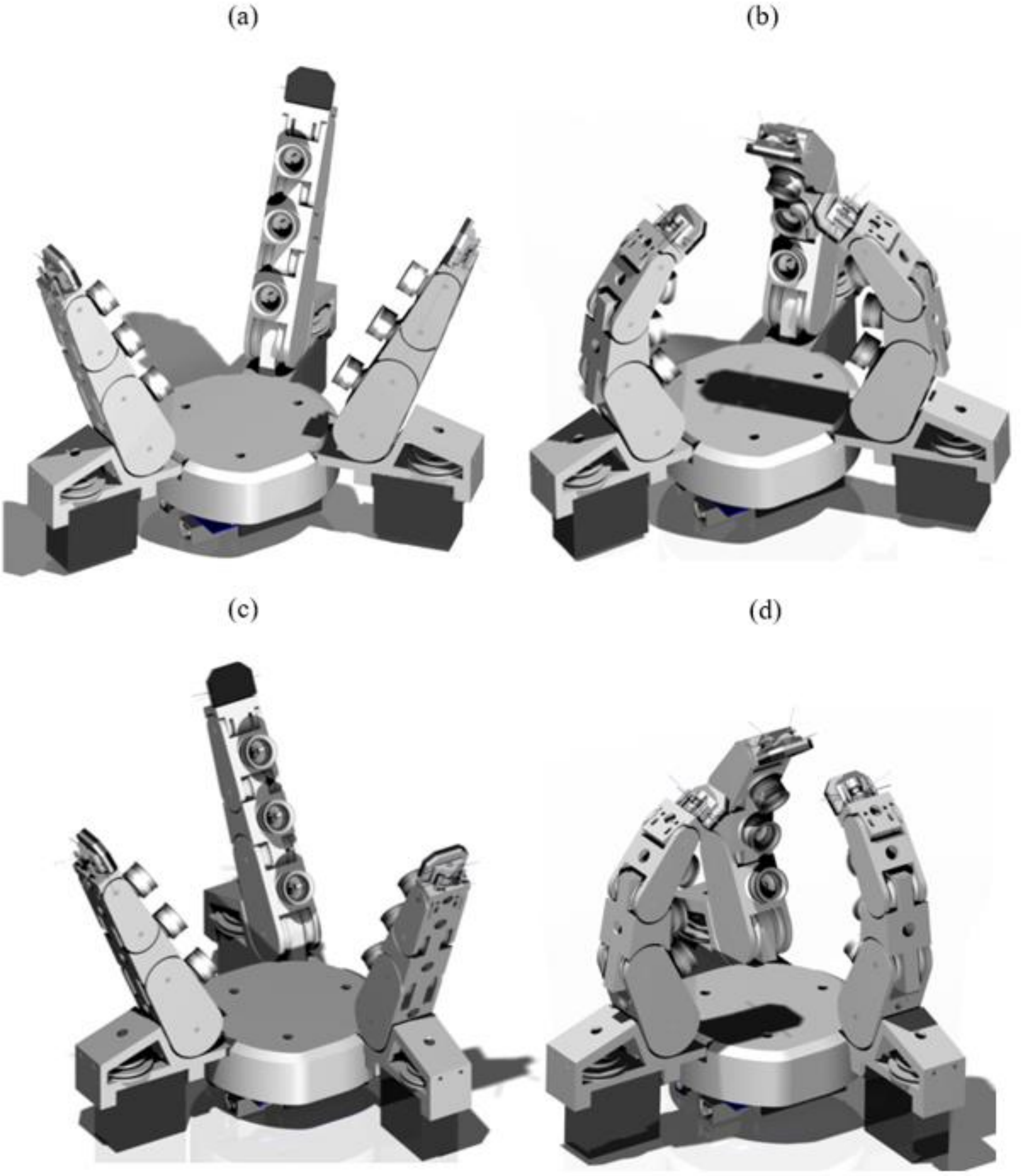


Figure 29: Final design of the fingered and suction grasping end-effector. (a) 120° degree idle pose. (b) 120° degree contracted pose. (c) Parallel pinch idle pose. (d) Parallel pinch contracted pose.

3.3.2 Manufactured Prototype

The end-effector was manufactured using Fused Deposition Modelling (FDM) 3D printing with PLA filament. This provided sufficient structural properties when tested with a 1.5kg mass and allowed for rapid prototyping. Axels were fabricated from stainless steel rods to provide low friction and strength in each joint. 6v DC servo motors with a 16kg/cm torque rating were used in each actuation system to provide the necessary force for force closure grasps. The components of the end-effector manufactured to date are shown in Figure 30.

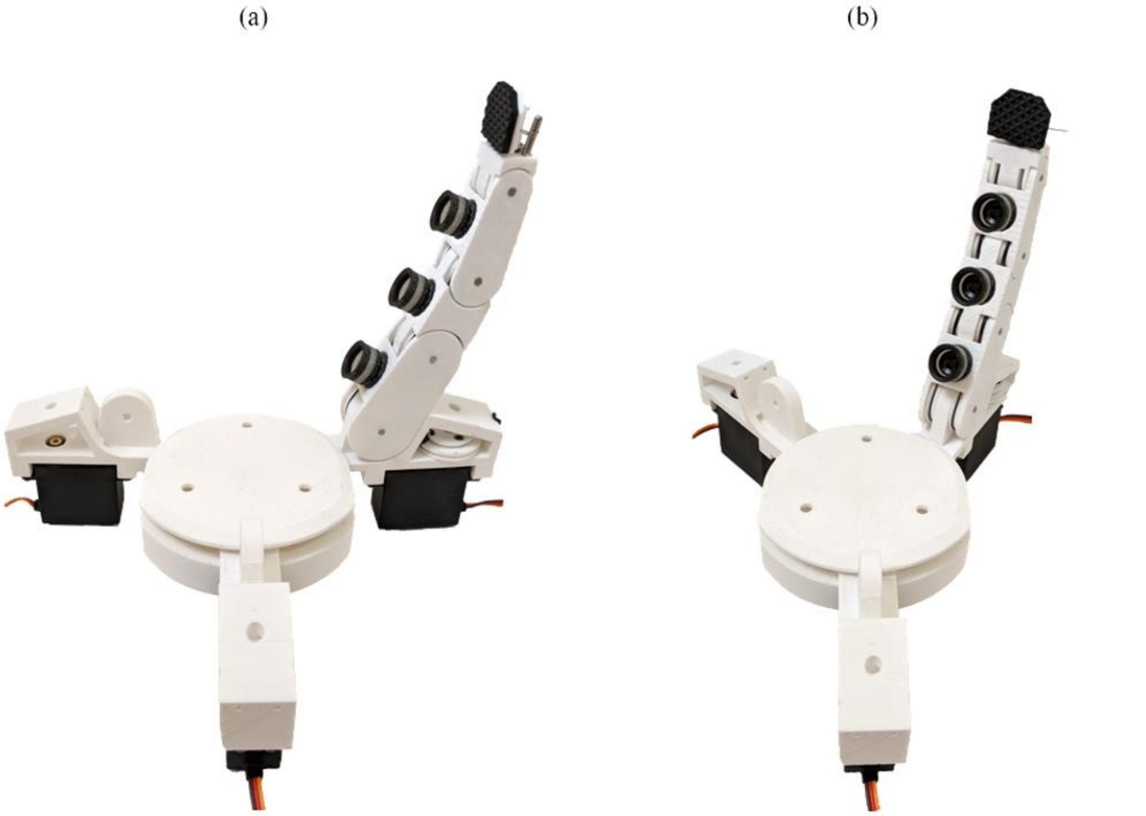


Figure 30: End-effector components manufactured to date (a) Parallel pinch grasp. (b) 120° degree grasp.

4 EXPERIMENTATION AND DISCUSSION

4.1 EXPERIMENTATION METHOD

To test the end-effectors efficacy at general-purpose grasping, an idealised bin-picking scenario is devised. This experiment challenges the end-effectors to perform robust grasping of a wide variety of objects and records its performance. In addition, it is necessary to validate the designs ability to exert high forces during grasping. Therefore, a blocked force test is used to determine the maximum force a finger is able to exert on the object.

4.1.1 Experiment 1: Idealised Bin-Picking Scenario

Setup

The experiment aims to emulate automated bin-picking by grasping a set of objects out of one plastic bin, then transfer them to another plastic bin placed one meter apart. To successfully challenge the end-effector with objects of varying material properties and geometrical complexity a carefully selected set of 25 objects were used. These objects closely reflect those used in the 2017 APC [8] and the ACRV Picking Benchmark [41] which were chosen for their ability to challenge end-effector designs.

Figure 31: Set of 25 objects used in the bin-picking experiment.

Object placement within the bins was chosen using stencils devised by the ACRV Picking Benchmark to ensure the placement and orientation was randomised. Once an object is placed in the bin the end-effector is lowered into the bin and a grasp is executed on the object. When a grasp has been attempted the end-effector is raised 30cm above the bin and moved horizontally to the second plastic bin one meter away at 10cm/s. This results in a transit time of 10 seconds and tests the grasps ability to withstand wrenches. Finally, the end-effector releases its grasp above the second bin. This is repeated for each object three consecutive times with the end-effector in three seperate modes, resulting in 9 attempted picks per item. Three differing modes were chosen to validate whether the optimised hybrid design yielded a better general-purpose grasping performance, these are as follows:

- Hybrid Grasping (Grasping and Suction):
  The proposed design is used to grasp the objects, thereby using both suction and grasping concurrently.
- Fingered Grasping:
  The suction cups are detached from the prototype and thus only fingered grasping is used to grasp the object.
- Suction Grasping:
  The servo motors in each finger are powered off and only suction grasping is used to grasp the object.

Measurements
To measure the performance of design, qualitative metrics were devised based on methodology outlined in the 2017 APC guidelines and metrics used to measure picking performance by Ocado Technologies [42]. These metrics are summarised in Table 2 and are used to compare the end-effector's performance in all three states (Hybrid, Fingered and Suction).

Measure	Description
Number of Successful Grasps (N_G)	The number of objects successfully grasped from the first bin and deposited in the second.
Number of Drops (N_D)	The number of objects initially grasped but then dropped during transit from the first bin to the second.
Number of Failed Grasps (N_F)	The number of objects the end-effectors was unable to securely grasp in the first bin.
Grasping Score (S_G)	This is an overall score that weights the recorded metrics and calculates an overall score for each mode of the end-effector. The weighting used rewards more successful grasps: $S_G \begin{cases} 0 = N_F \\ 0.5 = N_D \\ 1 = N_G \end{cases}$ Using a set of 25 objects at 3 attempts each for each end-effector mode, results in each mode grasping 75 objects. Therefore, each grasping score would have 75 measurement inputs.

Table 2: Summary of metrics used to evaluate end-effector's grasping performance.

Discussion
The experiment was expected to show an overall higher grasping score with the end-effector in its hybrid mode over the modes when fingered or suction grasping was used exclusively. Moreover, analysis on which objects were dropped (N_D) and which objects the end-effector failed to grasp (N_F) would demonstrate the strengths and weaknesses of each end-effector mode. It was expected in areas where failed grasps and drops occurred for fingered or suction grasping, hybrid grasping would prevail due to the optimisation undertaken in section 3.2.

The underactuated finger mechanism design was expected to help align the suction cups to the most suitable location for a high quality seal. Individual actuation was anticipated to allow the grasping of objects using unique strategies which would otherwise score as a failed grasp. Usage of self-sealing suction cups were predicted to show a demonstratable increase in suction force exerted by engaged cups over those not engaged. Adaptive fingertips were projected to help the end-effector perform precision pinches of smaller more contoured objects. Finally, the variable finger orientation mechanism was expected to allow the end-effector to grasp a wider range of objects shapes.

4.1.2 Experiment 2: Blocked Force Test

Setup
To determine the amount of force a finger is able to exert, a blocked force test is performed. The back of a finger was braced against a solid block with the tip of the finger slightly distanced from a force transducer. A transducer techniques model MLP-10 load cell was selected to measure the force based on reliable usage in previous blocked force tests [38]. Once setup, the servo motor is powered on and fully actuated. This results in the finger applying the force on the transducer, which is recorded untill the force peaks for five tests.

Measurements
The blocked force test measures peak force produced by the finger on five repeated tests, this is then repeated for each of the three fingers to ensure similarity. The median peak force of each finger is then used to calculate the end-effectors overall grasping force.

Discussion
The experiment was predicted to validate the end-effectors ability to securely grasp a mass of 1.5kg as outlined in section 0 as well as demonstrate similar force output across all fingers.

4.2 Discussion on Expected Overall Performance

The aforementioned experimental methodology is expected to validate the optimisation process outlined in section 3.2 and demonstrate key strengths of the novel design. Preliminary testing during the end-effector's manufacture, although not conclusive, did indicate this expected performance.

Additionally, the end-effector's performance is characterised by the improvement in grasping ability over the designs reviewed in section 2.3. As the end-effector combined strengths and mitigated weakness of each design reviewed, it was expected to exceed the strongest performing end-effector designs. In regard to speed, the responsive servo-motors and simple tendon pulley system used provided quick finger actuation exceeding the low grasping speeds seen by Cartman's Multi-Modal end-effector and the RBO Hand 2. The design also bolstered smooth finger closure unlike linkage based designs such as the iGRIPP 4 and Robotiq 3-Finger gripper whose closure was not smooth. The design also fell within the length constraints outlined in section 0 at a total end-effector length of 180mm providing a wide stroke size to encompass all objects commonly handled by humans.

Moreover, the varying finger mechanism mimicked the ability demonstrated by other end-effectors with similar finger orientation mechanism such as the iGRIPP 4 and Robotiq 3-Finger gripper. This allowed more adaptability in contrast to fixed finger pose designs such as RightHand Robotics GripperV5 which is considered the industry standard for hybrid fingered and suction grasping. The design was also made with robustness in mind and managed to grasp the 1.5kg load comfortably. Lastly, the high level of performance was achieved within the limited project budget making the grasper economically realisable for industrial solutions unlike high-end research focused designs such as the Shadow Dexterous Hand.

5 CONCLUSIONS

5.1 CONCLUSION

This work has sought to address the challenge of general-purpose grasping by proposing a novel end-effector design that is optimised for hybrid fingered and suction grasping. The following conclusions are drawn for each chapter:

- Section 2 – Literature Review on End-effector Designs:
  A thorough and consolidated literature review sought to understand the fundamental kinematics and mechanics principles used to achieve robust grasping. The review determined the underpinnings of current grasping technologies, strengths and weaknesses of notable end-effector designs and key surrounding work concerning grasping to reference throughout the end-effectors design.

- Section 3 – End-effector Design Methodology:
  An initial design using suction cups along the inner side of the fingers allowed the design to exploit form closure, force closure and suction grasping at once. Five features were then identified and designed to optimise the end-effector's general-purpose grasping performance: an underactuated finger mechanism; individually actuated fingers; self-sealing suction cups; adaptive fingertips and a variable finger orientation mechanism.

- Section 4 – Experimentation and Discussion:
  Two experiments are proposed to validate the end-effectors design and general-purpose grasping performance. An idealised bin-picking experiment is designed that measures the objects grasping performance of a set of 25 objects chosen from a number of picking benchmarks. The end-effector's performance is compared with the end-effector using grasping or suction only. This is supplemented by a blocked force test that aims to measure the maximum force each finger is able to exert.

5.2 FUTURE WORK

Having produced a hybrid end-effector design optimised for general-purpose grasping, it is apparent that there are also some limitations which serve to provide a foundation for future work. These include:

- Although individually actuated, the fingers could not react to the environment as a grasp occurred meaning only basic grasping strategies could be executed. Addition of a sensory system into the hand would allow for feedback and development of an intelligent control system to assist grasping in real time.

- The design lacked compatibility with robot arms commonly used in industrial installations and therefore limited the experiments which could be performed. Hence, creation of a forearm to embed the motors, pneumatic system and microcontroller with a universal fitting would allow for a more compact design and standard mounting on a robot arm.

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APPENDIX

2.1.4 Application Specific Grasping Approaches

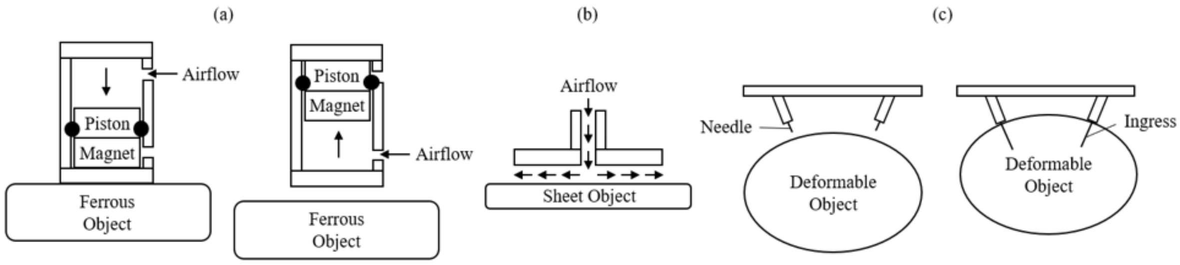

Figure 32: Illustration of three application specific grasping approaches. (a) Permanent magnetic grasping. (b) Bernoulli grasping. (c) Ingressive grasping.

In addition to the grasping technologies outlined in section 2.2, application specific grasping approaches were studied to determine if the technologies used could help guide the design of the hybrid fingered and suction grasping end-effector.

Magnetic Grasping

Magnetic grasping works similarly to suction grasping but can only be used with ferrous materials. There are two main categories of magnetic grasper: electromagnetic and permanent magnetic. Electromagnetic graspers use DC powered electromagnets to control the graspers magnetism and therefore grasp and release ferrous objects. Permanent magnetic graspers are unique in that they can grasp without any operational power, providing unique safety benefits. The permanent magnet is moved into contact and then separated from the ferrous object thereby grasping and releasing it [43]. This is usually achieved by using a mechanical pin or pressurised air as seen in Figure 32(a). Magnetic grippers offer many benefits such as high speed; the ability to grasp porous and flexible surfaces and do so with minimal power consumption.

Bernoulli Grasping

Bernoulli grasping uses the Bernoulli airflow principle to produce a grasping force. A high velocity airflow is ejected at the face of the end-effector creating an area of low pressure. The pressure difference between this area and atmospheric pressure exerts suction force on the object's face [44]. Due to the speed at which the air is ejected, a small pocket of air remains between the end-effector and the object's face as seen in Figure 32(b) allowing for non-contact grasping. As a result, Bernoulli graspers are often used to handle delicate sheet materials such as silicon wafers [45] but struggle with anything heavier and not flat.

Ingressive Grasping

Ingressive grasps take a unique approach by seeking to create an ingress in the object to hold it by. This is commonly achieved using needles that are inserted into the object at high speed as seen in Figure 32(c). The ingresses create a supporting structure around the needle thereby achieving a secure grasp similar to form grasping described in section 2.2.3. Since ingressive grasping depends on the objects internal structure instead of surface geometry it is used extensively in the handling of meat and has seen increasing use in other areas such as seed transplanting [46]. However, in most scenarios such as fruit and vegetables handling, the need to avoid inflicting damage on the object prevents the creation of ingresses.

3.1.3 Optimisation Objectives

From the literature review conducted on end-effector designs in section 2.3, four objectives were identified that reflect common factors considered by end-users when choosing an end-effector design:

- Robustness:
  A measure of how enduring the design is to continued usage and external forces. More robust designs are preferred due to their reliability, long operational life and reduced maintenance.
- Grasping Speed:
  The speed with which the end-effector is able to execute a grasp from an initial input to securely grasping the object. High grasping speeds are preferred as they result in greater overall operational efficiency.
- Compactness:
  A measure of how small the overall design is in all dimensions. More compact designs are often preferred for their increased dexterity and ability to approach grasps from otherwise obstructed angles.
- Stroke Size:
  The maximum size of object capable of being grasped. Larger stroke sizes allow for larger and therefore wider variety of objects to be grasped.

As some of these objectives are conflicting in nature a decision matrix was employed to rank their importance against the end-effector designs reviewed in section 2.3.

End-effector	Robustness	Grasping Speed	Compactness	Stroke Size
Cartman's Multi-Modal End-effector	2	2	1	2
RBO Hand 2	3	2	3	3
Shadow Dexterous Hand	3	4	5	3
Robotiq 3-Finger Gripper	4	4	4	4
iGRIPP4	3	3	4	2
RightPick Robotics GripperV5	4	3	3	3
Total Score (**Rank**)	19 (**2nd**)	18 (**3rd**)	20 (**1st**)	17 (**4th**)

Table 3: Decision matrix used to rank the importance of objectives used in the design process. Each rating uses a scale of 1 (Poor) to 5 (Excellent).

The resulting matrix can be seen in Table 3 where the objectives in rank of importance are: Compactness, Robustness, Grasping Speed and Stroke Size. Although not exhaustive, this ranking helped inform decision making when design limitations were encountered.