Project title:	Design and Accurate Control of a Novel Low-Cost Soft Robotic Arm for Soft Fruit Harvesting
Project number:	N/A
Project leader:	Philip Johnson, University of Lincoln
Report:	1st Annual report, October 2021
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Date project commenced:	1st October 2020

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[The results and conclusions in this report are based on an investigation conducted over a one-year period. The conditions under which the experiments were carried out and the results have been reported in detail and with accuracy. However, because of the biological nature of the work it must be borne in mind that different circumstances and conditions could produce different results. Therefore, care must be taken with interpretation of the results, especially if they are used as the basis for commercial product recommendations.]

AUTHENTICATION

We declare that this work was done under our supervision according to the procedures described herein and that the report represents a true and accurate record of the results obtained.

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PhD Student

University of Lincoln

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CONTENTS

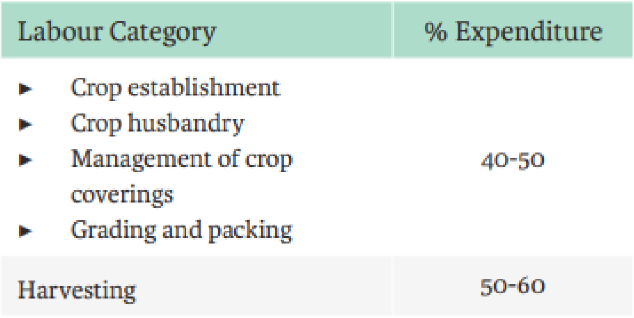
GROWER SUMMARY

Headline

A soft robotic harvester for strawberry picking could address the growing UK labour shortages while protecting the delicate handling of produce.

Background

The UK soft fruit sector is a substantial and growing industry under significant threat from a lack of seasonal labour. The majority of labour for the industry is comprised of seasonal workers with only a tiny fraction of the 29000 workers being UK nationals [1]. The availability of EU labour is decreasing rapidly due to restriction of 'free movement' following Brexit and the decreasing unemployment in eastern European countries which traditionally provided seasonal labourers e.g., Romania [1]. Labour costs already comprise around 50% of the cost of production, which is increasing due to inflation while the value of produce has remained relatively static [1]. More than half of this labour is used for the harvesting of fruit, additionally, jobs in soft fruit harvesting can be 'physically demanding, repetitive in nature, conducted in adverse environments and relatively unrewarding' [1][6].



Labour Category	% Expenditure
▸ Crop establishment ▸ Crop husbandry ▸ Management of crop coverings ▸ Grading and packing	40-50
Harvesting	50-60

Figure 1: Breakdown of labour involved in soft fruit industry [1]

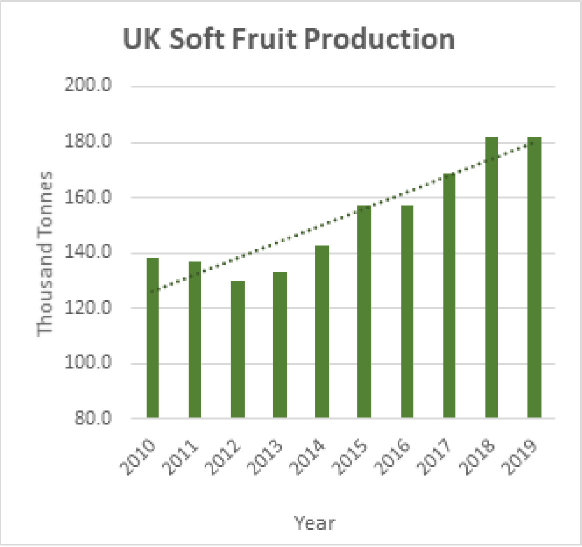


Figure 2: UK Soft Fruit production statistics. DEFRA Horticulture Statistics 2020.

Given these circumstances, there is a huge opportunity for developing robotics and automated systems to meet the needs of the soft fruit industry and wider agri-food sector. Selective harvesting as a research area has seen a huge increase amount of interest and funding in recent years, especially in the UK, resulting in the development of many associated technologies, however at the time of writing there aren't any commercially successful/viable solutions.

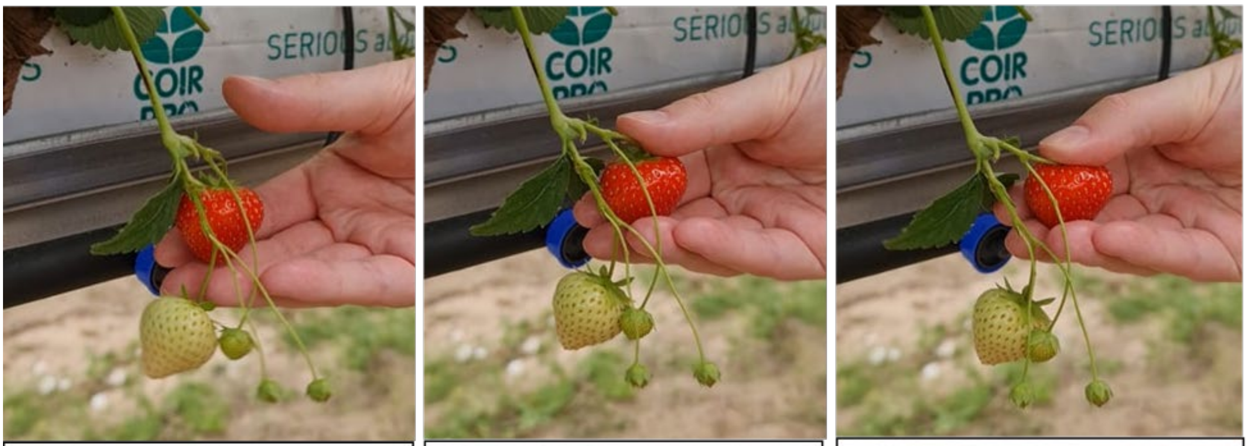
Automated manipulation and grasping of food items present a series of unique challenges compared to other sectors [6]. Firstly discrete, fragile items must be harvested individually without damaging or disturbing those around them in unknown/unstructured environments. Additionally, due to the high level of dexterity needed for picking, control systems are often required to be highly complex. There also exists a high likelihood of human-robot interaction and a resulting necessity for safety.

Summary

To build a suitable robotic harvester for picking soft fruits, we must understand the design challenge, and the necessary characteristics for producing a successful mechanism. Currently the favoured method in literature for robotic picking strawberries is to use a small pair of blades/pincers as part of the mechanism to cut the stem of a strawberry and carry the strawberry back to the punnet. This method is limited in its ability to interact with clusters of fruit and densely packed ripe strawberries hidden behind leaves and unripe fruit. The reasons for this limitation are first, that highly complex and precise motion planning is needed to position the cutting blades on the correct stem amongst a tangled web of similar stems. Secondly, moving any occluding unripe strawberries and generally interacting with the cluster is very risky with rigid manipulators, as the strawberries are very delicate and easily bruised. Any errors or inaccuracies hold potential for damage to the crop.

'Snap-picking' the fruit rather than cutting the stem could hold the key to addressing these limitations. The snap-picking method of picking strawberries is favoured by leading strawberry producers Berry Gardens Ltd, one of the UKs largest soft fruit growers. This picking method involves the human picker directly handling the fruit and rotating it to a 90° angle before pressing their thumb on the stem/calyx and pulling it away from the plant. The stem snaps with an audible 'pop' leaving little to no stem length above the leafy calyx.

Snap-picking Motion (Human Picker)



Stage 1
Supporting the strawberry from below

Stage 2
Applying pressure to the stem above the strawberry

Stage 3
Stem is now fully bent at 90°

Stage 4
Applying force, pulling the strawberry away from the plant

Stage 5
The stem snaps

Stage 6
The strawberry is carried to the punnet

Figure 3: The process of snap picking a strawberry

Simplifying the picking motion into these six stages highlights the desired three functions of the end-effector (Engulfing/grasping, applying pressure to bend stem, and pulling the fruit away from the plant). These three motions are listed in the next section in a table to map desired motions to necessary gripper characteristics.

The snap-picking technique could be replicated with soft robotic actuation, and this challenge forms the first research objective for this project. Rotating the fruit by 90° and applying pressure on the top of the stem could be achieved using custom shaped pneumatic channels which actuate the manipulator. The pulling of the strawberry while retaining soft material properties could be achieved with the assistance of variable stiffness methods, this will be further explored in year two of the project.

Using soft materials and soft actuators could also address the limitations of current robotic approaches, firstly because using soft compliant materials reduces the need for highly accurate motion planning, since these systems can passively adapt to unknown environments and any errors or inaccurate motions are less likely to cause damage to plant/other fruit. Additionally, using soft materials make interacting with clusters viable and brushing against/moving other unripe fruit is possible because the soft materials are inherently safer.

The major motion challenges to address for achieving this research objective are tilting the stem 90°, increasing the speed of actuation and applying a force to the top of the strawberry to snap the stem.

SCIENCE SECTION

1. Introduction

1.1 Motivation

Considering the identified requirements for a robotic harvesting manipulator it has been proposed that soft robotics may have great potential in this application [6]. Soft robotics is a relatively new branch of robotics which uses compliant materials and soft methods of actuation/sensing to develop, often entirely, deformable robots. A soft robotic harvesting manipulator could address many of the current difficulties with robotic harvesting of soft fruits. Firstly, the use of compliant, deformable materials results in a manipulator which can handle delicate soft fruits more safely and is much less likely to damage other untargeted fruits/obstacles in the process of harvesting. This property means that soft robotic manipulators can be more robust in dealing with the uncertain/unstructured environments presented by agriculture. Additionally, human-robot interaction could be achieved more safely with soft deformable system also being less like likely to cause injury to humans working alongside harvesting robots. Finally, the development of compliant manipulators and grippers could also simplify the design of agricultural robots by reducing the need for complex visual and tactile sensors, as the safety in interaction with clusters of fruit reduces the need for motion precision [6].

Soft robotics for agriculture is a very recent, emerging field and presents an open area of research which highlights the timely nature of this project.

1.2 General Aims and Objectives

The generalised aim of this research is to develop and control a novel, low-cost, soft robotic arm manipulator for harvesting strawberries. The arm should ideally be suitable for deployment on a separate mobile robotic platform. The simplified aims of this research are as follows:

1. Design a novel end-effector based on soft robotic technologies that can harvest delicate strawberries without causing damage to other obstacles such as unripe fruits and leaves.

2. Design a low-cost manipulator arm which is self-supporting, able to apply enough force to snap-pick strawberries and which is suitable for deployment on a mobile robotic platform.

3. Develop a non-linear robust controller to enable the manipulator to harvest strawberries while compensating for the unknown forces resisting picking and disturbances caused by other untargeted fruit/leaves interacting with the end effector.

2. Materials and methods

2.1 Design of a Novel Soft-robotic End-effector

2.1.1 Research question

How can a soft robotic end-effector, using pneumatic actuators, replicate the manual snap-picking technique of strawberries within clusters without bruising target or neighbouring strawberries?

Measurable objectives:

- **Snap-picking**: The gripper specifications needed for snap-picking include: 90° tilting motion, swallowing behaviour to support the fruit on all sides, and the ability to adapt to shape/size variations. These specifications will be verified using test rig to quantify bending angle, speed, and adaptation to varying fruit sizes, later testing in field (manually held) on grown strawberries to verify snap effect.
- **Navigating clusters**: Maintaining compact size of end-effector to reach a target strawberry within a cluster. Working to miniaturise actuator technology as much as possible.
- **Without bruising**: Soft actuator and body with no hard/sharp components to enable safe interaction with strawberries. Engulfing/swallowing behaviour rather than cutting will also support this aim. Verified using shelf-life testing and comparison with quality standards for human pickers.

2.1.2 Problem Summary

A major component in exploring this research question is the understanding the design challenge proposed, and the necessary characteristics for producing a successful end-effector. Currently the favoured method in literature for robotic picking strawberries is to use a small pair or blades/pincers as part of the end-effector to cut the stem of a strawberry and carry the strawberry back to the punnet. This method is limited in its ability to interact with clusters of fruit and densely occluded fruit (Figure 4). The reasons for this limitation are first, that highly complex and precise motion planning is needed to position the cutting blades on the correct stem amongst a tangled web of similar stems. Secondly, moving any occluding unripe strawberries and generally interacting with the cluster is very risky with rigid manipulators, as the strawberries are very delicate and easily bruised. Any errors or inaccuracies hold potential for damage to the crop.

Figure 4: Clusters of strawberries, (Captured at Clock House Farm, Kent UK)

‘Snap-picking’ the fruit rather than cutting the stem could hold the key to addressing these limitations. The snap-picking method of picking strawberries is favoured by leading strawberry producers Berry Gardens Ltd, one of the UKs largest soft fruit growers. This picking method involves the human picker directly handling the fruit and rotating it to a 90° angle before pressing their thumb on the stem/calyx and pulling it away from the plant. The stem snaps with an audible ‘pop’ leaving little to no stem length above the leafy calyx.

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The snap-picking technique could be replicated with soft robotic actuation, and this challenge forms the first research objective for this project. Rotating the fruit by 90° and applying pressure on the top of the stem could be achieved using custom shaped pneumatic channels which actuate the manipulator. The pulling of the strawberry while retaining soft material properties could be achieved with the assistance of variable stiffness methods, this will be further explored in year two of the project.

Using soft materials and soft actuators could also address the limitations of current robotic approaches, firstly because using soft compliant materials reduces the need for highly accurate motion planning, since these systems can passively adapt to unknown environments and any errors or inaccurate motions are less likely to cause damage to plant/other fruit. Additionally, using soft materials make interacting with clusters viable and brushing against/moving other unripe fruit is possible because the soft materials are inherently safer.

The major motion challenges to address for achieving this research objective are tilting the stem 90°, increasing the speed of actuation and applying a force to the top of the strawberry to snap the stem.

2.1.3 Informing the Design

To gather information for the design of the end effector and generate initial ideas, the first step taken was a week-long placement with one of the UK's largest soft fruit farms 'Clock House Farm' (Kent, UK). It was important to see how a working strawberry farm is arranged in person and learn from the behaviour of the fastest human pickers. Being trained to pick the fruit and getting a feel for the characteristics and dynamics of real strawberry plants, by spending a day picking, was hugely important in forming ideas about picking mechanisms. Prior to the placement, most resources available favoured cutting the stem above the strawberry. At Clock House Farm, all strawberries are 'snap-picked' and according to their picking manager and the head of R&D at Berry Gardens, this method is 10% faster and increases shelf life.

Several video resources were collected during the Clock House farm placement, demonstrating the best practice in 'snap-picking'. These methods used by the fastest 'champion' pickers will inform the next stage of producing design concepts and prototyping for the end effector. Breaking down the ideal snap-picking method into individual motions and poses is a good way of assessing the range of motion required and setting desired poses for a novel end-effector to replicate. Other types of motion used when picking strawberries will still be considered and it will be worth investigating whether other farms which are not under the Berry Gardens group use the same method of picking or whether there are variations.

Figure 5: Clock house farm polytunnel

Figure 6: Clock house farm strawberries from below

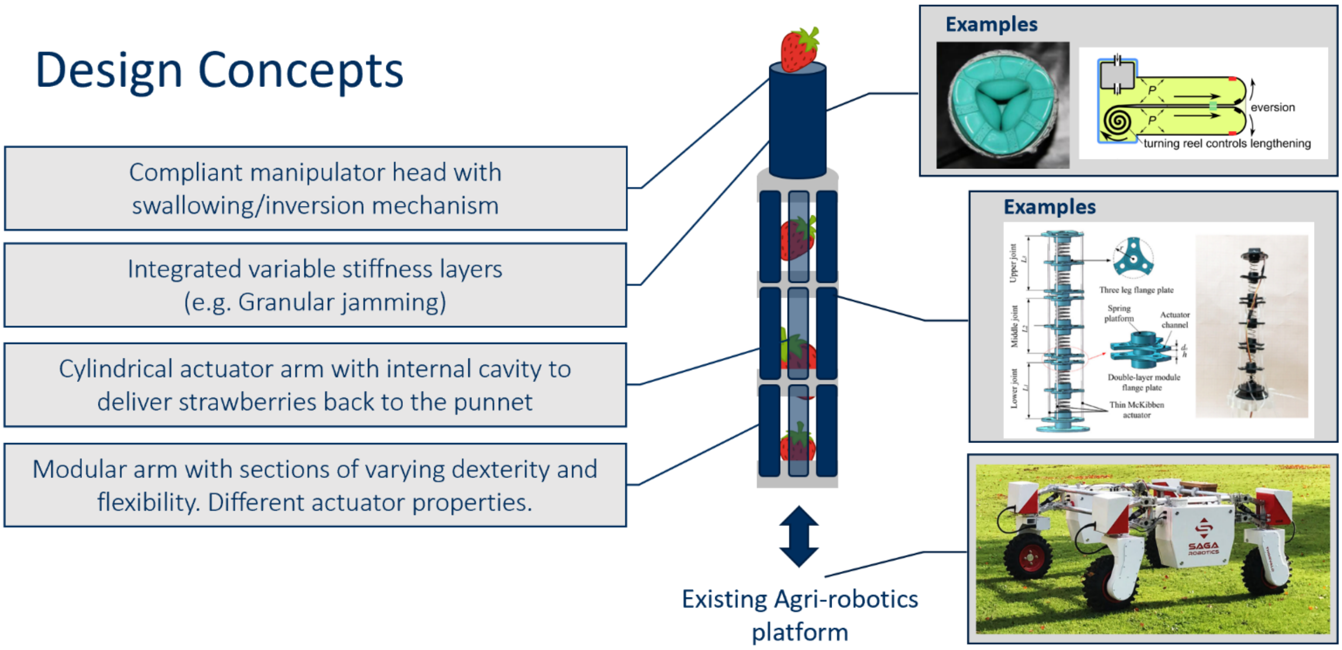
Additionally, a placement week with the National Institute of Agricultural Botany, engaging with strawberry breeding/trait experts was very useful in understanding the properties of the target fruit to be picked. A very wide range of traits, which influence the picking challenge, depend on the specific cultivar of the strawberries. For example, the ease of snap picking is a measured trait as well as the length of peduncle (stem) above the fruit and the grouping/clustering of fruit on the plant. Information on these plant properties and specific trends within strawberry breeding will inform the design of the end effector because they are properties of the environment the end effector will operate in.

2.1.4 Initial Design Ideas for this Research Objective

Following the literature survey, the most appropriate type of actuator for the action of the end effector is the Fluidic Elastomer Actuator. It is proposed that with a cylindrical shaped swallowing mechanism, the manipulator could engulf the strawberry, and distribute force around the fruit rather than using a gripper with individual fingers, concentrating force on small pressure areas. Using a pneumatic elastomer-based design for this end effector would mean that the entire end of the manipulator is deformable, as it would be made of a soft silicone elastomer and actuated by pneumatic air pressure chambers. Pneumatic actuation has the potential to produce highly complex motions through the shaping of air chambers rather than using several joints. Based on the average shape of a strawberry, a picking head could be developed which inflates to passively adapt to fruit shape. A tilting mechanism which fuses the body/materials of the end effector with function could then rotate the strawberry 90° to decrease the force needed to snap the stem and detach the strawberry. It is also possible that twisting the stem could decrease the force needed for snapping but this would need to be determined with an additional force sensing trial.

Table 1: Mapping Task Requirements to Gripper Specifications

Task	Detail	Gripper
Grasp/engulf	**Adapting to a range of strawberry sizes** **20-30mm**	**Soft swallowing behaviour**
Pressing/ bending stem	**90° tilting of picking head**	**Custom pneumatic channels shapes**
Pulling	**Stability /response to external forces**	**Variable stiffness, e.g. tendon jamming mechanism**



The main difficulty in designing the end effector is introducing a stem snapping system. Although it is possible to snap-pick a strawberry without bending the stem, it is beneficial to bend the stem at 90° to significantly reduce the amount of force required for snapping. An example of how this can be achieved is featured in Figure 7 however, as we can see, this existing method is bulky and unsuitable for interacting with clusters of fruit. There is, therefore, room for improvement and miniaturisation in building upon this concept. To reduce the size of the of the end effector the initial approach is to involve an element of morphological control to achieve snap picking behaviour without a complex mechanism. The concept of engulfing and swallowing the strawberry could assist with this motion if the elastomer encloses on top of the fruit, applying pressure to the stem similar to a human picker.

Figure 7: ©Octinion Rubion Strawberry harvester

2.1.5 Plan for Investigating this Research Objective

The current plan to explore this research question is to follow a standard design development process such as the example in Figure 8.

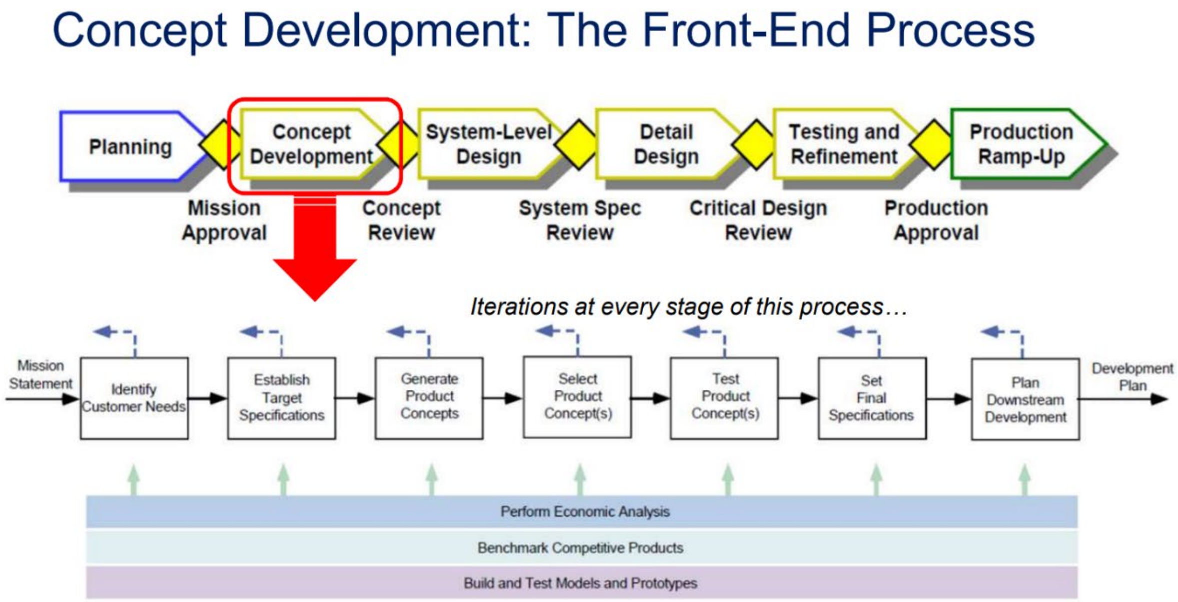


Figure 8: Concept development process. (Ulrich, K.T. and Eppinger, S.D. (2008) Product Design and Development. 4th Edition, McGraw-Hill, New York)

1) Concept Generation and Selection

Several initial concepts will be produced for evaluation which use soft robotic principles such as biomimicry and inspiration. Those with the most potential for achieving the research objective and favourable traits will be selected for prototyping and testing.

2) Prototyping and Testing

After selecting the best design concepts with the greatest potential, elements of their design can be prototyped using 3D printing, silicone moulding and CAD modelling etc. Their ability to achieve a range of poses can be tested alongside pictures and videos of human hands snap-picking correctly. A test rig can also be assembled with fake/real strawberries to test force application and grasping in different mock scenarios.

3) Refinement

The best design can be taken forward and improved upon based on testing. This end-effector design will be the first section of the overall manipulator design.

2.2 Using Variable Stiffness to Increase the Force Applied by the Soft Manipulator

2.2.1 Research Question

How can we increase the value of force applied by a soft robotic manipulator on a strawberry using an integrated tendon-jamming variable stiffness mechanism, while maintaining compactness?

Measurable Objectives:

- **Force applied:** We can measure the value of force applied by the manipulator using a test rig with force/torque sensors and determine success in increasing force. Average force needed for snap picking ~3.71N (should be further investigated with experiments for the final novel end effector design).
- **Variable Stiffness:** To evaluate the effects of the variable stiffening mechanism we can measure the dexterity and stiffness of the manipulator in its unstiffened state and ensure that these properties are preserved, as well as determining the range of stiffness of the mechanism. The speed of actuation of this mechanism should also be measured and refined ensuring that the mechanism developed is appropriate for fruit harvesting.
- **Compactness:** It is important that the variable stiffness mechanism developed should not make the end effector too heavy or bulky. These characteristics will be measured, and efforts will be made to minimise them but locating actuation power at the base (e.g., electric motor driving the tendons).

2.2.2 Problem Summary

Applying force with a soft robotic manipulator is inherently more difficult than with conventional rigid robotic manipulators. Compliant, deformable structures cannot transfer forces as well as rigid structures so the best solution for a soft robotic system is to increase stiffness/rigidity when a manipulator is required to apply a strong grasp (high force). To achieve a high picking force to pull strawberries and snap their stems it is important to increase the amount of force the picking head can apply. To achieve this aim in soft robotics, there are several 'variable stiffness' methods used to increase the stiffness of manipulators when needed, and maintain soft, deformable properties when these properties are more desired. The literature review has shown that 'jamming' mechanisms will be the most appropriate choice for this project. The average force required for snap-picking is 3.71 N with appropriate picking method [3]. The literature review has also shown that variable stiffness methods such as granular jamming can be used to successfully increase the stiffness of a soft robotic manipulator, resulting in reduced deformation under the same loading. One of the main challenges of this research aim is miniaturising a variable stiffness mechanism to be integrated into the end effector. This challenge could contribute to a gap in literature because most variable stiffness mechanisms exist as large ‘proof of concept’ devices rather than being miniaturised/utilised.

2.2.3 Informing the Design

I have completed a variety of lab work which directly relates to this research objective concerning the fabrication of tendon-jamming variable stiffness actuators, force generated by soft robotic devices and the measurement of forces and loads supported by the actuators.

One project involved the fabrication and testing of a soft pneumatic actuator with a braided tendon-jamming core for variable stiffness. The actuator built upon the design of the STIFF FLOP actuators for minimally invasive surgery. The tendon core was attached to a stepper motor designed to twist the tendons into a rigid knotted state, increasing the stiffness of the actuator. The project was initially proposed with synergies for this PhD project and several directly transferable skills were developed as a result. Firstly, the fabrication of the soft elastomer actuator with a tendon-jamming core, including 3D printing moulds with multiple adaptations and revisions, has provided experience for the same steps which will be involved in the prototyping for this project. Skills gained will be useful in developing similar variable stiffness mechanisms for testing. Images of some of the project components are included in Figure 9.

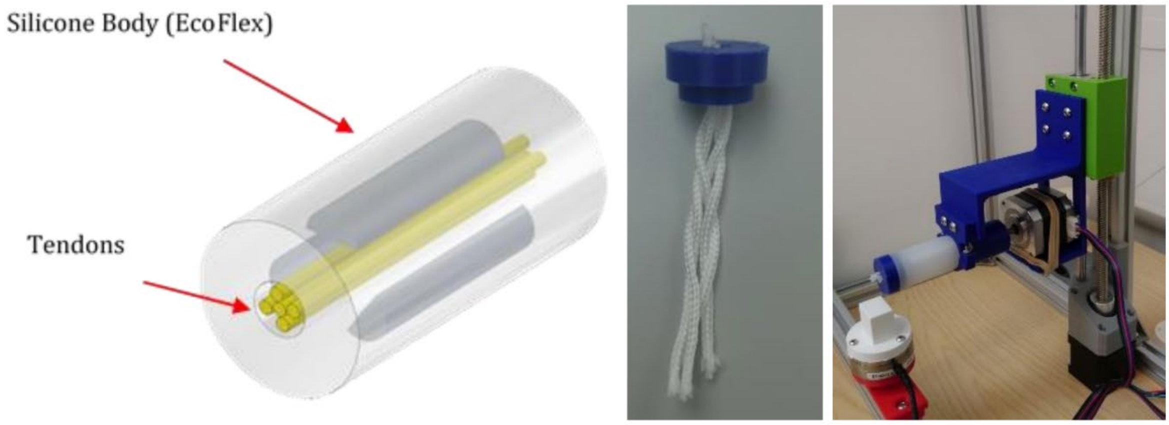


Figure 9:(Left to right, CAD model of actuator, braided tendon core, test rig with stepper motor and force/torque sensor). Paper accepted for TAROS conference 2021

Secondly the testing of the variable stiffness actuator using the custom force/torque rig is valuable experience when considering how to test the performance of variable stiffness in this PhD project. We investigated both the resistance to deformation under a series of loads, and the capacity of the actuator to apply force to a force/torque sensor in jammed and unjammed states. This testing is a simplified approximation of the kind of testing I plan to conduct in this project, with the more specific application of strawberry picking forces.

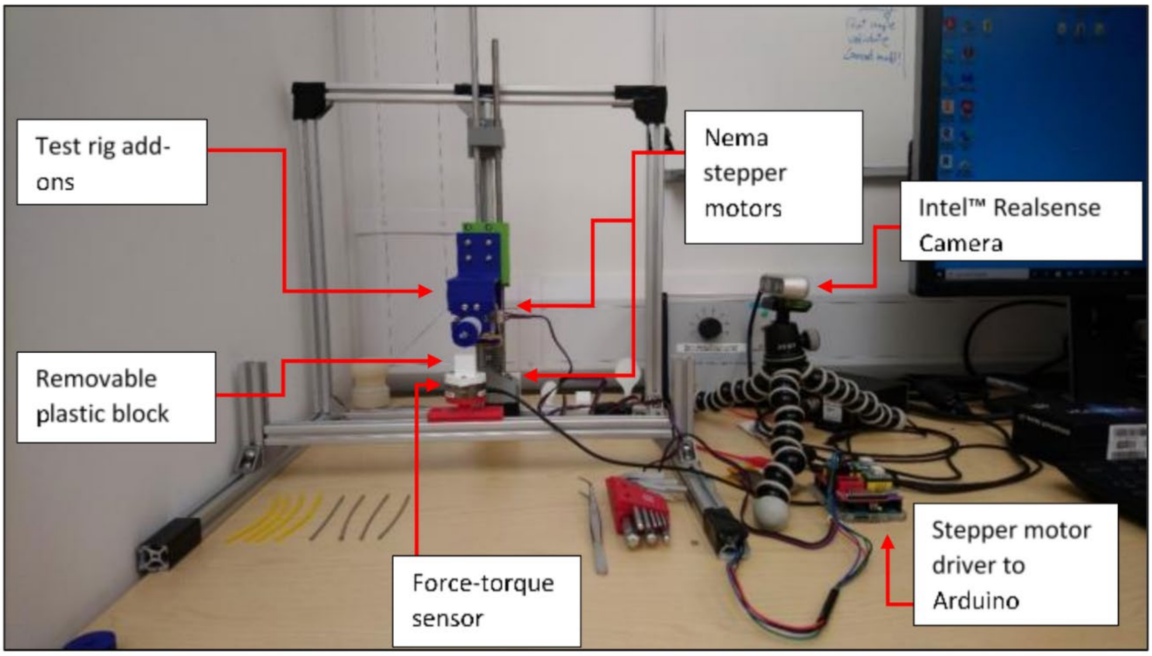


Figure 10: Force/torque test rig, University of Lincoln, photo and labels by William King

Finally, this project required the development of a pneumatic control system for the inflation of the actuator channels. Transferable skills were gained with the use of a pneumatic pressure regulator, solenoid valves, flow control devices and writing Arduino scripts to control these components.

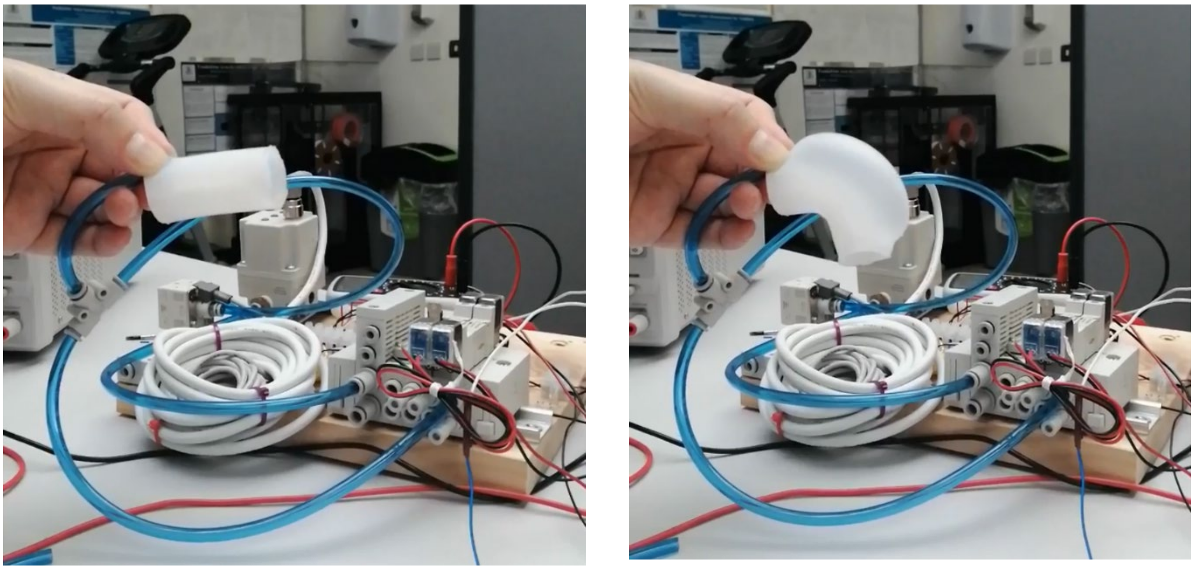


Figure 11: The soft elastomer actuator deflated and inflated, pictured with pneumatic equipment

The control script/circuit we developed was successful in controlling multiple solenoid valves to inflate and deflate more than one pneumatic chamber. This experience involved the refinement of flow control to increase the speed of actuation and was important in highlighting how fast pneumatic actuators can work with appropriate air pressure and flow channelling.

2.2.4 Initial Plan for Investigating the Research Objective

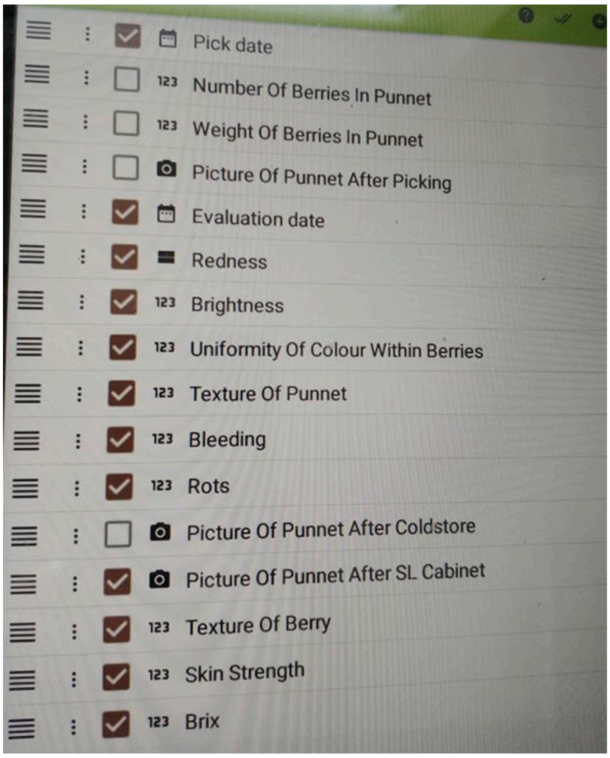
To investigate this this research objective, I plan to develop an integrated stiffness layer using fibre/tendon jamming depending on the favoured/final design of the picking end-effector. Miniaturising these variable stiffness devices represents a gap in the current literature as most variable stiffness concepts exist only in research trials and are mainly very bulky unrefined mechanisms (with the exception of granular jamming). An example of how this integration could work for a cylindrical shaped swallowing gripper would be a braided sheath of fibres and tendons which could be tightened or loosened by a motor at the base of the manipulator depending on the desired properties. This action would squeeze the flexible gripper increasing its stiffness. The goal of this development would be to produce a novel method of tendon jamming which is highly effective in increasing stiffness while remining more compact than other variable stiffening solutions.

Any variable stiffness mechanism produced will be evaluated using a series of force testing experiments to determine deformation under load and the amount of force which can be applied after integrating a stiffening device. Other work which will inform the design of experiments for testing this research objective involved the testing of the grasping strength of a soft robotic gripper. In this project I completed several weeks of friction/force experiments to determine the grip strength of a novel fin-ray finger. The gripper finger was actuated by a stepper motor to produce movement along the z-axis, the resultant force applied to an object, was determined with a force/torque sensor. A similar experiment could be used to evaluate gripping forces with and without stiffening mechanisms in this project and the experience gained can inform improvement to experimental design.

Shelf-Life Testing

Some berries don’t release from the plant as easily as others. The grip and firmness of the harvesting could damage the berry or plant if the strawberry picking robot holds on too firmly. Or the strawberry could slip from its grasp if the grip is not firm enough. Increased force applied to the strawberry comes with the drawback of potentially causing bruising to the delicate flesh of the fruit. To determine the effects of these forces, I plan to conduct shelf-life assessments based on those I took part in during my placement with the National Institute of Agricultural Botany (NIAB). These shelf-life assessments are developed with industry and can be used to confidently assess the impact of picking forces on shelf life compared to fruit picked by human pickers.

The shelf-life assessments involve an assessment of fruit properties after picking and after 3 weeks of cold storage. The assessment includes properties such as colour, level of bruising, skin strength, rotting and the general texture. The scores on these properties before and after cold storage are specific to the tests conducted. Figure 12 shows a list of tested characteristics compiled in an app used by NIAB.



- ☑ Pick date
- ☐ 123 Number Of Berries In Punnet
- ☐ 123 Weight Of Berries In Punnet
- ☐ Picture Of Punnet After Picking
- ☑ Evaluation date
- ☑ Redness
- ☑ 123 Brightness
- ☑ 123 Uniformity Of Colour Within Berries
- ☑ 123 Texture Of Punnet
- ☑ 123 Bleeding
- ☑ 123 Rots
- ☐ Picture Of Punnet After Coldstore
- ☑ Picture Of Punnet After SL Cabinet
- ☑ 123 Texture Of Berry
- ☑ 123 Skin Strength
- ☑ 123 Brix

Figure 12: A series of characteristics measured by NIAB to determine soft fruit shelf life.

2.3 Developing the Manipulator Control System

2.3.1 Research Question

How can control stability be maintained with the assistance of variable stiffening, when pulling strawberries and applying force?

Measurable objectives:

Stability: The settling time and response of the system will be an indicator of the stability.

Error: Feedback control action uses an error signal, which is the difference between the desired output (set point) and the system output (measured value).

2.3.2 Problem Summary

The modelling and control of non-linear deformable materials is much more challenging than with rigid systems. Using materials such as silicone elastomers also increases the likelihood that actuators will not have homogeneous material properties and may behave unpredictably. Despite this, using soft materials also holds some opportunities for control, because larger margins for error are acceptable when materials are deformable and less likely to cause damage with imprecise motion. Because the gripper will grasp using inflation of a deformable material, the gripper will also be able to passively adapt to different shapes and sizes of strawberries without relying on accurate control to make tiny adjustments to a rigid picking head for every strawberry.

The major challenge is maintaining stability of the manipulator when unknown external forces and disturbances are applied by the resistance of the strawberry plant. Once a stem is snapped, separating the strawberry, the controller must quickly account for this sudden change in external forces and stabilise the manipulator. Picking speed must be increased as much as possible whilst maintaining stability as picking speed is one of the most important metrics in the performance of a harvesting robot.

The control system is dependent on the final end effector produced and the most appropriate sensors to integrate into its design. Fruit localization and environmental perception is beyond the scope of this project and several groups at the University of Lincoln are already working on vision systems.

2.3.3 Informing the Design

To prepare for the controller design challenges in this project I completed a course called: Modern Robotics, Course 1: Foundations of Robot Motion, provided by Northwestern University. The course introduced robot configurations, for both serial robot mechanisms and robots with closed chains, the task space and configuration space, degrees of freedom, C-space topology, implicit and explicit representations of configurations, and holonomic and nonholonomic constraints. The next step in preparation for the control challenge will be to gain greater understanding of motion planning and path planning algorithms.

The first experience gained with pneumatic control was building a pneumatic controller with an Arduino Uno for soft robotic lab experiments. A compressor with a controllable pressure regulator was controlled using a potentiometer and monitored with a digital pressure sensor. An Arduino script was also written to activate solenoid valves in sequence to inflate and deflate multiple pneumatic chambers

2.3.4 Initial Ideas for Meeting this Research Objective

I intend to explore options for delivering the strawberries from the picking head back to the base of the manipulator without moving back and forth from plant to punnet. This vastly reduces the demand for highspeed motion/trajectory planning and the associated difficulties with dynamic stability. If the soft picking head can be used to swallow the strawberries, a channel or belt could be used to transport them to the base of the arm which would avoid a large amount of motion pathing and trajectory planning completely. The motion planning problem may then be reduced to moving from target strawberry to target strawberry and matching the pose/orientation of the fruit.

Picking forces can be modelled as external unknown forces acting on the manipulator. The most important control challenge for picking will be the point at which the stem snaps and the resistive force of the plant is immediately removed. The manipulator must be able to maintain stability when faced with this sudden disturbance. Detecting this external disturbance quickly with lightweight sensor is important for fast picking. A novel approach for this challenge could be to detect this snapping with a microphone rather than an expensive force sensor. The audible pop could be distinguished from background noise using a highly sensitive microphone rather than using a force sensor because high precision force sensors are expensive and bulky.

3. Results

As this project involves design and testing of a novel robotic harvester, the first year has been centred around learning technologies and gaining experience with fabrication processes needed for the prototyping and development of early design concepts. In the last few months, we have begun developing a prototype soft joint which will be used in the testing stages of the manipulator in June-September growing season 2022. The manipulator will be comprised of several novel elements which will be individually tested.

The significant findings and results of this project will be determined in the second half of the four years, however substantial amounts of early testing data will be available in the second annual report in October 2022.

The insight and industry information gathered from formal interviews with experts and berry gardens growers is currently being developed into a paper on the potential applications for soft robotics in the UK soft fruit industry.

4. Conclusions

- Soft pneumatic-type manipulators are the most appropriate subset of soft robotics for use in the soft fruit sector
- Working in strawberry polytunnels alongside human pickers is vital in informing the design of a robotic picking arm
- 3D printing moulds for casting of silicone parts in an effective low-cost method to produce components for the harvesting manipulator.

5. Knowledge and Technology Transfer

18th November 2020 – AHDB Soft Fruit Technical Day

25th November 2020 – CTP Autumn Event

25th – 27th January 2021 - AHDB Crops Conference

12th April 2021 - Soft Robotics in Agriculture Workshop RoboSoft 2021, Cornell University

6th July 2021 - CTP Summer Event

8th July 2021 - Lincoln Agri-Robotics Mini Conference

13th July 2021 - Festival of Fresh

6. Glossary

Manipulator - A robotic device which interacts with objects without physical contact from the operator

Actuation/Actuator - A component of a machine that is responsible for moving a mechanism or system

End-effector - A device at the end of a robotic arm designed to interact with the environment

Motion Planning - The process of breaking down a desired movement task into discreet motions

Calyx - The green leafy material on the top of the strawberry

Cultivar - A plant variety produced by selective breeding

Peduncle - The stalk/stem bearing a strawberry

Morphological Control - Incorporating control behaviours into the shape or design of a robot

Elastomer - An elastic polymer material

Solenoid - An electromechanically operated valve

Biomimicry – Design modelled on biological entities

7. References

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