Design of a Novel Mechatronic Fatigue Testing System to Test the Functional Lifespan of a Compliant Mechanism Kiwifruit Gripper-End Effector Device

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Abstract

There is limited research into the fatigue life of compliant mechanisms, and a lack of standardised equipment to fatigue test such structures. This paper presented PneuGrip 2, a novel mechatronic fatigue testing system designed to fatigue test compliant mechanism robotic kiwifruit grippers. The design of its interacting mechanical, electronic, and control systems are outlined. A compliant gripper is fatigue tested for one million cycles, replicating the forces experienced in a typical harvesting motion. The compliant mechanism showed no degradation in performance after the test. While the study demonstrated a promising lifetime for the gripper, further testing is required to establish statistical significance and fully quantify its service life.

1 Introduction

Kiwifruits are the most valuable horticultural product contributing to the economy of Aotearoa New Zealand. In 2024 kiwifruit accounted for 73 percent of the country's fruit exports and was valued at $3.5 billion [1]. Promisingly, the kiwifruit industry is set to grow; the New Zealand Ministry of Primary Industries projects continuous growth of kiwifruit export revenue values until at least 2029 [2].

Unfortunately, due to several factors the kiwifruit industry has been experiencing labour shortages [3]. This is a problem that is only set to worsen, given a projected 23 percent increase in labour demand from 2023 to 2028 [4]. Currently, the industry relies entirely on human labour for harvesting fruit. With an increasing shortage of kiwifruit harvesters looming, the New Zealand economy is at severe risk of losing a significant portion of its value.

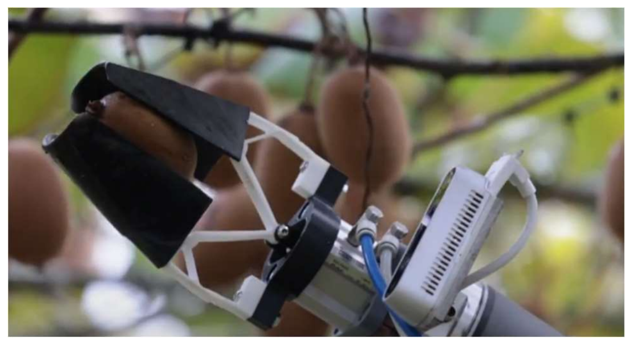


Figure 1: A compliant mechanism robotic gripper-end effector device equipped on a UR5e harvesting kiwifruit in the field [10].

One promising avenue for filling in the forecasted labour shortages is by automating the fruit harvesting process. While technical viability has been shown, the technology has not been adopted commercially, and progress is needed to reach commercial viability. An important part where progress can be made is the end-effector. Monolithic compliant mechanism robotic grippers offer several advantages over their traditional rigid body counterparts. These include cheaper manufacture and operation, reduced part counts, looser maintenance requirements, and higher precision due to the absence of backlash [5]. Even so, an essential, but challenging, consideration in the design of compliant mechanism devices is their fatigue life.

Since the relatively recent emergence of compliant mechanisms in engineering academia [5][6], numerous novel machines have been realised to

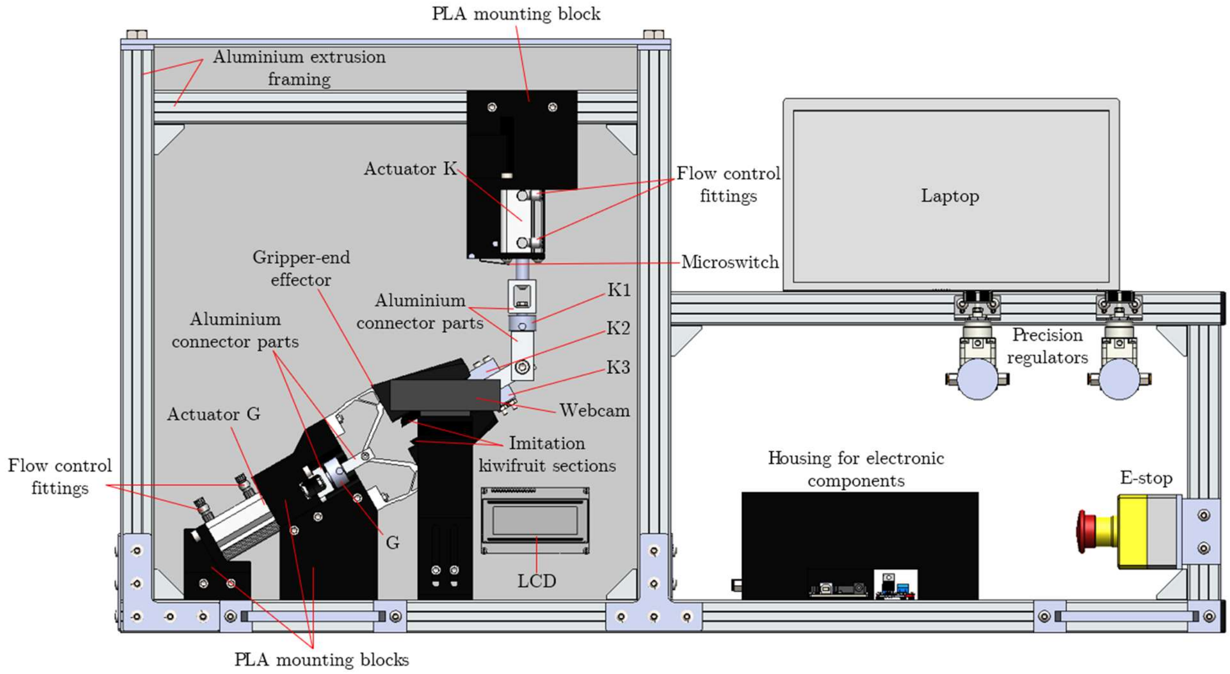


Figure 2: Labelled front view of PneuGrip 2.

experimentally test the fatigue life of various compliant mechanism systems. These include bistable electric switches [5][7], flexure hinges used in micromanipulators [8], and compliant polymer specimens whose sole purpose is to be fatigue tested [9]. The custom-made machines for these systems cannot possibly be used to fatigue test entire compliant kiwifruit gripper structures, and until now no machine has existed for this purpose.

Figure 1 shows a compliant mechanism gripper-end effector device that has been developed and successfully used to harvest kiwifruit [10]. However, it is unknown whether the device can remain functional after repeated use in the harvesting season. If kiwifruit orchardists are to be convinced to adopt this novel technology, the device's functional lifespan must be investigated experimentally. A novel mechatronic fatigue testing system, named PneuGrip 2, was designed for this very purpose.

This paper outlines the design of PneuGrip 2 and its interacting mechatronic systems to meet the following functional requirement: test the functional lifespan of the gripper-end effector device. Then, the experimental setup, and results of a 1 million cycle test are presented and evaluated. Ultimately, the aim of this work is to definitively determine whether the gripper-end effector device can maintain functionality – after having been subjected to cyclic loading representative of the real-world kiwifruit harvesting application.

2 PneuGrip 2 Design

PneuGrip 2, shown in Figure 2, is an experimental mechatronic fatigue testing system designed to test the functional lifespan of compliant mechanism kiwifruit gripper-end effector devices.

2.1 Mechanical System

Figure 3 illustrates the compliant-end effector device tested in this study. The gripper was developed with a topology optimization design methodology. It was manufactured via selective laser sintering on a FORMIGA P 110 Velocis and is made of PA2200. The end effectors were 3D printed on a Phrozen Sonic Mini 8k out of Resione F80 elastic resin.

Whilst undergoing fatigue testing, the gripper-end effector is to grasp an imitation kiwifruit assembly, shown in Figure 4A. The kiwifruit sections were 3D printed on a FDM printer out of PLA at 100% infill. The kiwifruit sections were modelled through a series of extruded cuts out of a CAD model of a mean kiwifruit (Fig 4B). Table 1 presents the mean physical dimensions of 10 green and 10 gold kiwifruits collected from PFR and Te Puke orchards (located in Waikato and Bay of Plenty regions respectively).

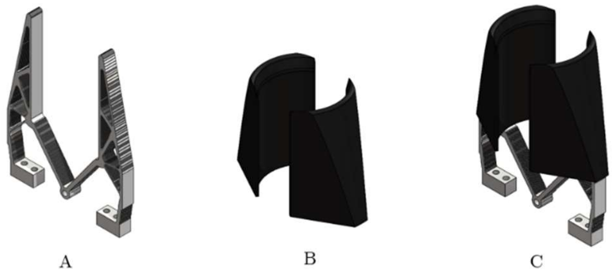


Figure 3: A: PA2200 topology optimized compliant mechanism gripper. B: Elastic resin end-effectors. C: Complete assembly of gripper-end effector device constituting the test sample.

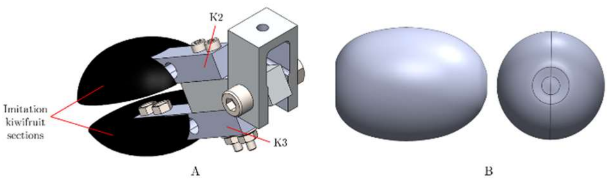


Figure 4: A: Assembly of imitation kiwifruit. B: CAD model of mean kiwifruit.

Table 1: Mean physical dimensions of 10 green and 10 gold kiwifruits collected from PFR and Te Puke orchards.

Physical Dimensions	Gold in PFR	Green in PFR	Green in Te Puke	Overall
Mean Length (mm)	76.01	73.21	67.72	72.31
Mean Diameter (mm)	55.47	54.50	51.91	53.96
Mean Stem Length (mm)	41.76	57.28	N/A	49.52

The geometry of the mean kiwifruit CAD model is based on the overall mean length and diameter calculated from the kiwifruit measurements. The imitation kiwifruit assembly is designed to have the same mean diameter and stem length of kiwifruit based on the overall physical properties in Table 1.

Two SMC CDQ2A25-25DCZ pneumatic cylinders are used to actuate the gripper (Actuator G) and apply a force to the imitation fruit to simulate picking forces (Actuator K). Both actuators are equipped with flow control valves to manually tune the speed of the cylinders. Air is distributed to the pistons using two SMC SY3140-5LOU spool valves and pressure is regulated by two SMC IR1020-01H-A precision regulators.

The gripper is mounted onto Actuator G using an FDM printed PLA mounting block at 100% infill. Similar mounting blocks are used to mount Actuator K and Actuator G to the machine's framing. Several connector parts link the numerous components of the Actuator G and Actuator K assemblies and were hand machined out of 6061-T6 aluminium on a vertical milling machine.

Aluminium extrusion is used for the structural framing and allows for the easy repositioning of other mechanical components. This enables the testing of not only different gripper-end effector designs but also permits testing at different grasp angles; it would simply be a matter of designing and 3D printing proprietary mounting blocks for a given gripper design and desired grasping angle.

Figure 5 illustrates the kinematics of a fatigue testing cycle. In State 1, both Actuator G and K are extended, the gripper is open and ready to grasp the imitation kiwifruit. In State 2, Actuator G is retracted, which closes the gripper and causes it to grasp the imitation kiwifruit. In State 3, the gripper remains closed while Actuator K is retracted, this pulls the imitation kiwifruit assembly upward, simulating the robotic arm lowering to pick kiwifruit off the vine. Finally, State 4 has both Actuator G and K extended back to their initial State 1 positions, ready to repeat the cycle.

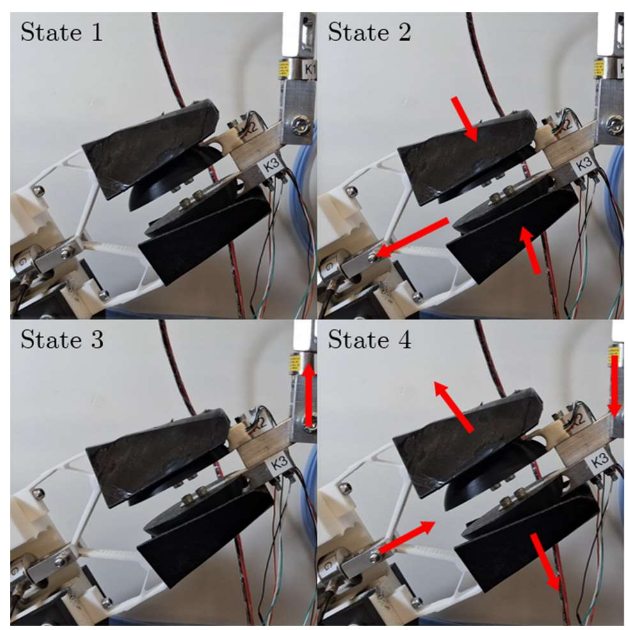


Figure 5: The 4 states of a fatigue testing cycle.

2.2 Electronic System

PneuGrip 2 employs four load cells to obtain quantitative data indicative of the sample's functional performance. Each load cell possesses their own designation; K1, K2, K3, and G (Fig 2). K1 is a 10kg tension load cell which monitors Fruit Detachment Force (FDF); this is the downward force causing a kiwifruit to detach from the stem during harvesting. K2 and K3 are both 10kg cantilever load cells. These are mounted on by the imitation kiwifruit sections (Fig 4A) and are used to monitor the output force of each gripper finger. G is a 20kg tension load cell which monitors the input force of Actuator G to close the gripper.

An Arduino Mega2560 Rev3 microcontroller handles I/O operations. At the end of each test cycle, an LCD is updated to display the force readings from all load cells, the number of test cycles, the time (in seconds) elapsed since the test began, and the recorded frequency of each cycle. This data is also written onto a micro-SD card after every cycle.

PneuGrip 2 has four HX711 load cell amplifiers (one for each load cell), and two IRF520 MOSFET drive modules (facilitating the switching of the pneumatic spool valves). A Honeywell V15T16-CZ100 microswitch is mounted onto the Actuator K mounting block such that it is switched if the actuator's piston rod is fully retracted during the test; this constitutes a catastrophic functional failure of the sample (Fig 6). The machine also features an E-stop for when a test is required to be stopped quickly and safely.

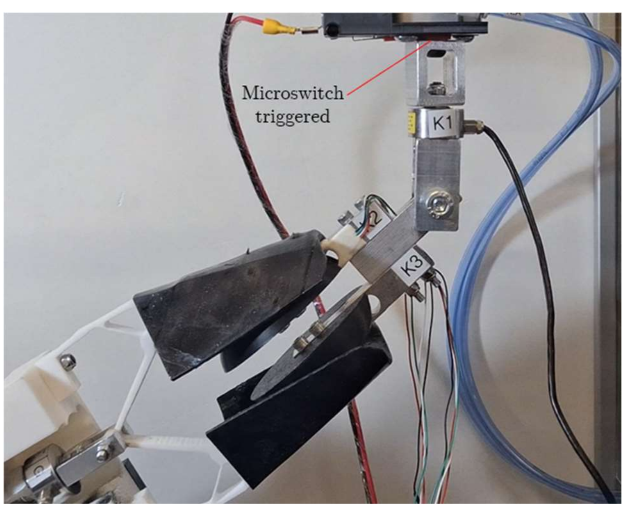


Figure 6: Example of a catastrophic functional failure of the sample causing the microswitch to trigger.

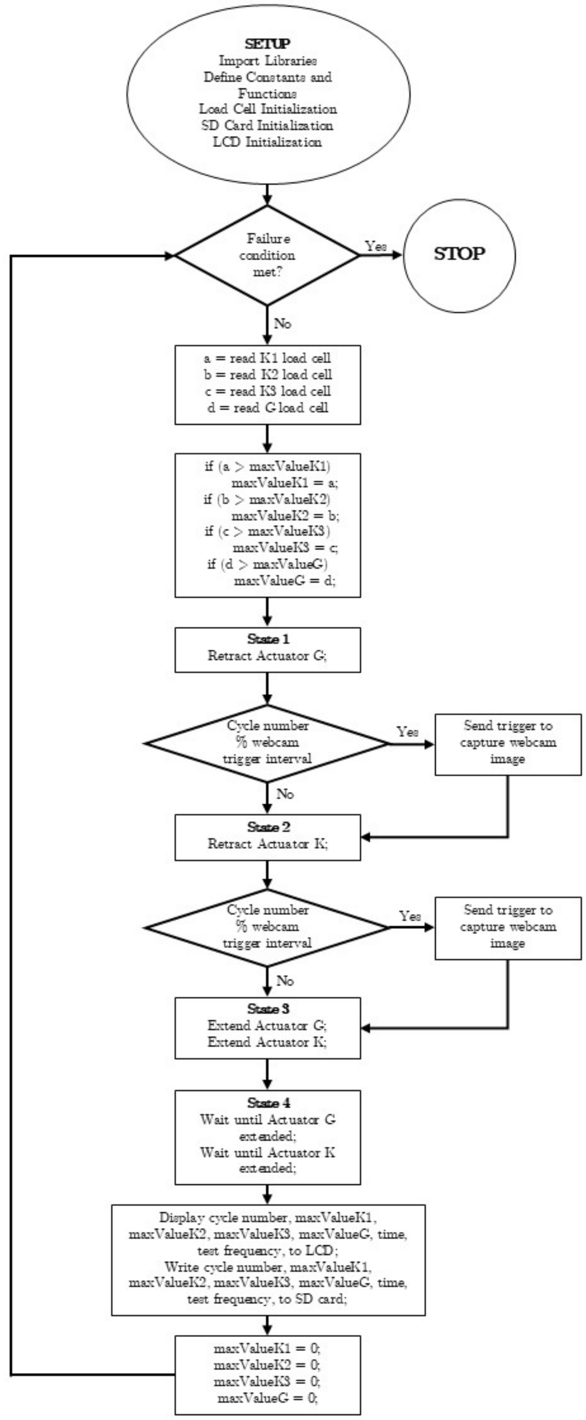


Figure 7: Flow chart of state machine executed by the Arduino Mega2560 Rev3.

A Grandstream GUV3100 webcam is used to capture images of the test sample at the end of State 2 (after the imitation kiwifruit has been grasped) and then again at the end of State 3 (after the imitation kiwifruit has been pulled upward). These images can be analysed to determine whether slippage has occurred between the imitation kiwifruit and the end effectors. In the field, slippage between the end effector and kiwifruit causes damage to the kiwifruit skin. This would be considered a functional failure of the gripper-end effector device as it would make the kiwifruit unsuitable for export.

2.3 Control System

An Arduino sketch and a Python script run in parallel to control the interaction between PneuGrip 2's mechanical and electronic systems. The Arduino sketch, illustrated as a state machine flow chart in Figure 7, is executed by the Arduino Mega2560 Rev3. Its primary responsibility is to run the state machine and control the pneumatic actuators. It also gathers force readings from the load cells and logs them onto the SD card and LCD. The programme is written such that the maximum force values sampled after each cycle are logged.

The state machine terminates if one of the following 3 failure conditions are met: 1) the limit switch is activated indicating catastrophic functional failure (Fig 6), 2) the E-stop is pressed, or 3) a user sends "stop" through the PC serial monitor. The Arduino programme also streams load cell data and control prompts via USB serial into the Python script. This script is responsible for logging backup load cell data, triggering the webcam to capture images, and realising a Graphical User Interface displayed on the laptop screen (Fig 8).

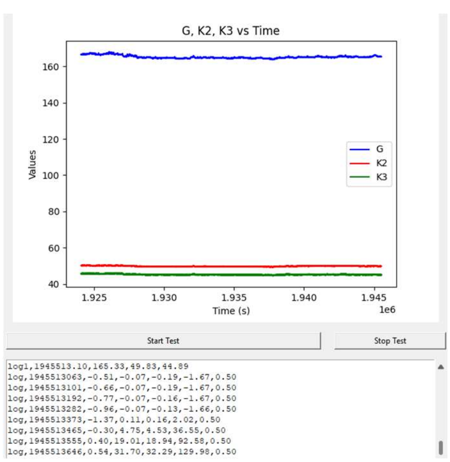


Figure 8: GUI which shows a graphical representation of maximum force readings gathered from load cells G, K2, and K3 from the last 100 cycles, and a live numerical feed displaying the time (in milliseconds), force readings from K1, K2, K3, and G, and the recorded test frequency.

3 Experimental Setup

The gripper-end effector sample was prepared for testing by equipping it onto PneuGrip 2 as shown in Figure 2. The sample was mounted at a grasp angle of 60°. Grasp angles ranging from 60° to 90° reduce the tendency for slippage and are thus more commonly used in the field [11].

The air pressures at the piston rod actuators were set via the precision regulators. The air pressure for Actuator G was set at 5.0 Bar. This pressure is the maximum operating pressure at which the gripper-end effector device is used in the field. It is thus representative of the worst case for stressing the gripper when it is used during normal operation. The pressure for Actuator K was set at 1.0 Bar, and the resulting theoretical pulling force from the actuator at the end of State 3 is 37.78 N. This ensures that the pulling force is always greater than the maximum required fruit detachment force at 60°, which was calculated to be 27.46 N, and the sample can be said to have successfully picked a kiwifruit after every test cycle.

The webcam was set to capture images of the sample every 5 cycles. This was to lessen the digital storage requirements on the HDD drive which was used to store all the captured images.

The testing cycle frequency was set at 0.5 Hz. The test cycle period is time-based, whereby for every cycle each state would be executed within a constant set time. The sample was tested for a total of one million cycles.

4 Results and Discussion

4.1 Inspection of Mechanical System and Sample

The mechanical components of PneuGrip 2 did not experience any catastrophic failures which would have rendered the test invalid. However, as shown in Figure 9, the gripper side aluminium connector parts did experience abrasion wear leaving filings on the mounting block. Nonetheless, this observed wear did not significantly impact the functionality of the sample; the connector parts can be considered as consumables to be replaced when required.

The sample withstood the entire test without experiencing catastrophic functional failure (Fig 6). Then the sample itself was unequipped from PneuGrip 2 and was inspected for

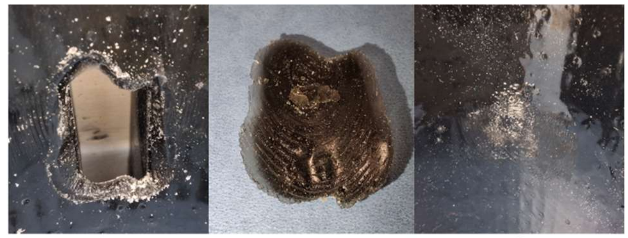
Figure 9: Filings that fell onto the gripper mounting block because of abrasion of the aluminum connector parts.

physical damage. As shown in Figure 10A, the gripper did not experience catastrophic material failure and was completely intact after testing. Figure 10B illustrates the physical damage to the end-effectors. There was significant damage to the K2 side end-effector where a piece of resin had broken off from the component. This can be considered a catastrophic failure of the part (Fig 11A and 11B). The K3 side end-effector experienced merely surface wear (Fig 11C). In the field, the lifespan of the end-effectors can be extended by intermittently switching the orientation of the gripper when harvesting so that there is even wear on the end-effectors. This result shows that the end-effectors will fail earlier compared to the gripper; an end-effector like that shown in Figure 11A will have a greater tendency of causing damage to kiwifruit skin. Thus, future work can involve investigating of how many cycles the end-effectors can last before catastrophically failing.

A B

Figure 10: A: The gripper after testing showing no sign of catastrophic failure. B: Pictured left to right is the damage to the K2 side and K3 side end-effectors respectively.

The observed uneven wear on the end-effectors is expected. This given for every cycle the K2 end-effector experienced a greater maximum reaction force, with the K2 imitation kiwifruit section being pulled up against the end-effector. The opposite is the case for the K3 end-effector, in which the K3 kiwifruit section was pulled with the end-effector, resulting in a lesser reaction force on the end-effector and thus causing less wear.



A B C

Figure 11: A: Close up image of surface damage to the K2 side end-effector. B: Close up image of the resin piece which broke off the K2 side end-effector. C: Close up image of surface wear on the K3 side end-effector.

4.2 Load Cell Data Results

Microsoft Excel was used to process the load cell data. Outliers in the load cell data, due to errors in the load cell readings, were identified and filtered out from the dataset. All other remaining data points would be included in plotting graphs. Linear regression models and R^2 values of the plots were obtained to supplement the discussion of the results and are tabulated in Table 2.

Table 2: Linear regression models and R^2 values obtained from load cell datasets.

Dataset	Linear Regression Model	R^2 Value
K2 vs Cycle	y = -2E-06x + 53.146	0.1057
K3 vs Cycle	y = -8E-07x + 47.854	0.0346
G vs Cycle	y = -6E-06x + 177.02	0.1366
Average of K2 and K3 vs Cycle	y = 0.2025x +7.8667	0.2003

The cause of the uneven wear on the end-effectors is evidenced in Figure 12 which plots the maximum gripper finger output (which is equivalent to the reaction force acting on the end-effectors) for K2 and K3 side grippers against the number of test cycles. Throughout the entire test the K2 side gripper finger consistently output a greater finger force compared to the K3 side gripper finger. The linear regression models show that there was no significant trend in the output forces of both gripper fingers; with gradients of -2E-06 and -8E-07 (unit: Newtons per cycle) for K2 and K3 side fingers respectively. This suggests no significant degradation in the gripper fingers' performance throughout the entire test. The

R^2 values for the datasets, (0.1057 and 0.0346 for K2 and K3 fingers respectively) demonstrates significant variance in the force output; it is almost certain there is no correlation between the gripper fingers' force outputs and the number of times they are cycled.

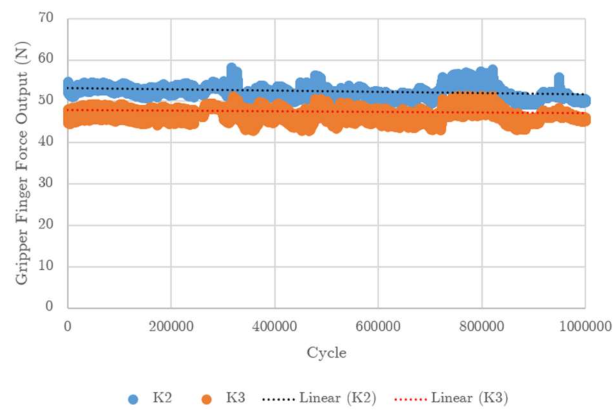


Figure 12: Gripper finger force output vs Cycle

Figure 13 shows the maximum input force of Actuator G causing the sample to grasp the imitation kiwifruit assembly per cycle. Like the finger force output profiles, there appears to be no clear downward trend of the input force, with the linear regression resulting in a gradient of -6E-06 Newtons per cycle. This indicates sustained functional performance of the gripper's input point (the part of the gripper which is linked to the piston), and the reliable performance of Actuator G. Like the dataset shown in Figure 12, there was also significant variance in the input force, with the regression producing an R^2 value of 0.1366. It is almost certain that the number of cycles the sample was tested for does not explain the input force.

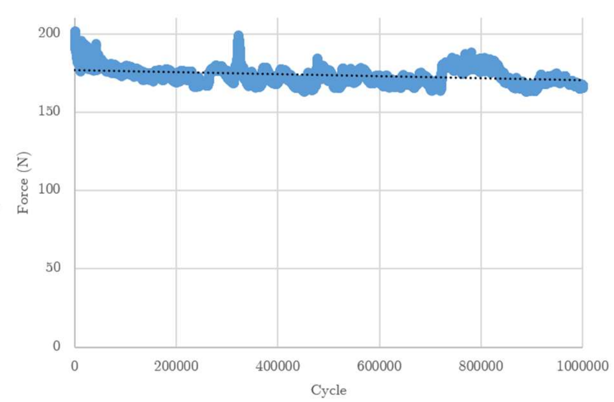


Figure 13: Actuator G input force vs Cycle

The K2 and K3 gripper finger output forces were averaged and then plotted against the Actuator G input force (Fig 14). The gradient produced from the linear regression model was 0.2025, indicating proportionality between the Actuator G input force and the gripper finger output forces. The R^2 value of the regression model is 0.2003, greater than those obtained for the plots in Figures 12 and 13. It is thus more likely that the Actuator G input force explains the force outputs of the gripper fingers, rather than the number of test cycles. However, there remains doubt behind this postulation given the significant variance observed in the dataset.

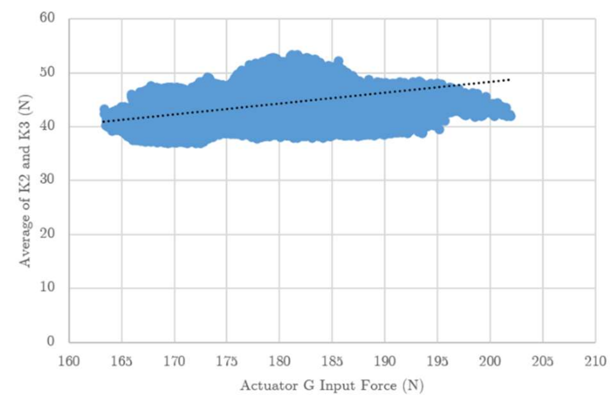


Figure 14: Average of K2 and K3 vs Actuator G input force.

While not appearing to trend downwards, the datasets presented in Figures 12 and 13 show significantly high variance – with irregular fluctuations in the force plots. These forces are directly related to air pressure delivered to the pistons. Therefore, it can be reasoned that the compressed air supply caused the fluctuating forces via the irregular distribution of air. Which could have resulted from the loading and unloading of the central pneumatic system's air reservoir – and is ultimately an uncontrollable factor given changing demands on the central pneumatic system. Yet another cause of inconsistent air pressure delivery is the fact that PneuGrip 2, during testing, shared its air supply with another machine via a tee fitting. This machine also used piston rod actuators which were actuated independently to those of PneuGrip 2. This disrupted air pressure delivery to PneuGrip 2.

Curiously, these fluctuations were present despite the application of precision regulators between the central pneumatic system and PneuGrip 2's spool valves (which then delivered air to the pistons). This suggests imperfections in the manufacturing and assembly of the regulators' componentry; this however is mere speculation. Notwithstanding of this peculiarity, the fluctuations in air pressure did not severely hinder the fundamental task of the sample, which is to pick kiwifruit by producing a sufficient FDF.

Shown in Figure 15 are the instances throughout the test where K1 was recorded to be below 27.46 N, and the sample is considered to have failed to pick a kiwifruit. These instances occur sporadically, and at varying timespans; there appears to be no pattern behind these failure occurrences. It cannot be said that the sample's performance throughout the test degraded such that it reached a point in time where it continuously failed to produce an insufficient FDF. In fact, beginning from cycle 926,628 the sample consistently produced the sufficient FDF until the conclusion of the test. Further analysis of K1 data reveals the sample produced an FDF greater than or equal to the required 27.46 N for 962,252 of the 1 million cycles, which is a 96% successful picking rate.

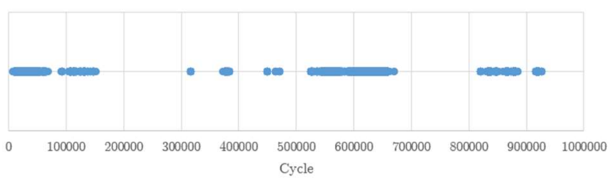


Figure 15: Instances when K1 recorded force values below the required FDF of 27.46 N.

The K1 load cell is attached to Actuator K, which shares the same air pressure supply as Actuator G. Given this, it is likely that the cause of the FDF failure instances are the irregularities in air pressure delivery – as was previously discussed to explain, possibly, the fluctuations in the force data sets in Figures 12 and 13.

4.3 Webcam Captured Image Results

After the conclusion of the test, the sets of images captured by the webcam (taken at the first cycle and last cycle) were collected for analysis to quantify any slippage which may have occurred. The images were imported into SolidWorks using the Sketch Picture tool and scaled such that the geometry of the sample in the digital workspace matched what they are in reality. Figure 16 shows the sketch lines that were drawn onto the imported images, and the parameters measured using the Smart Dimension tool. Table 3 shows the measurements of the slippage parameters for every image analysed.

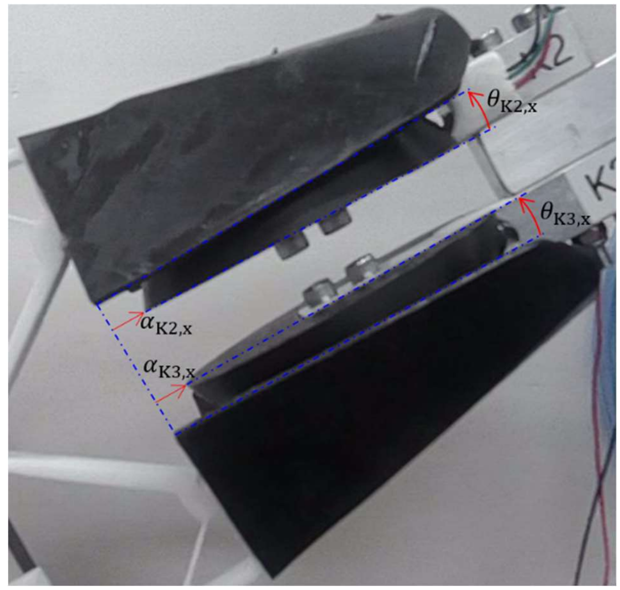


Figure 16: Sketch lines and parameters measured to quantify slippage. Direction of arrows indicate positive direction. The subscript x refers to either the first or second image taken.

Table 3: Slippage parameter measurements

	α_{K2}	α_{K3}	θ_{K2}	θ_{K3}
Unit	mm		degrees	
First Cycle, 1st Image	7.72	6.90	2.29	1.15
First Cycle, 2nd Image	7.64	6.96	1.78	2.40
Last Cycle, 1st Image	7.39	6.68	2.14	2.40
Last Cycle, 2nd Image	7.58	6.50	1.67	2.96

Defined are two parameters to quantify slippage. The first is stroke, which is the rubbing of the imitation kiwifruit sections against the end-effector along its longitudinal direction. The second is roll, which is the relative rotation of the imitation kiwifruit with respect to the end-effectors. For both first and last cycles, each imitation kiwifruit side (K2, or K3) will have a stroke and roll value associated with it. Stroke and roll were calculated (Table 4) using the equations below, where subscript b denotes the kiwifruit side (K2 or K3).

$$Stroke_b = \alpha_{b,2} - \alpha_{b,1}$$

$$Roll_b = \theta_{b,2} - \theta_{b,1}$$

Table 4: Calculated stroke and roll values for the first and last test cycles.

	$Stroke_{K2}$	$Stroke_{K3}$	$Roll_{K2}$	$Roll_{K3}$
Unit	mm		degrees	
First Cycle	-0.08	0.06	-0.51	1.25
Last Cycle	0.19	-0.18	-0.47	0.56

Comparing the slippage values between the last and first cycles, there is a notable change in magnitude of stroke; 0.27 mm and 0.24 mm for K2 and K3 sides respectively. Doing the same comparison for roll, $Roll_{K2}$ changes in magnitude significantly less than $Roll_{K3}$; 0.04° and 0.69° respectively. These results indicate a reduction in performance of the sample with respect to slippage, as both stroke and roll increase in magnitude as the sample is cycled.

Due to time constraints, only the first and last cycles' images could be analysed to obtain the slippage parameter results. However, future work can involve the analysis of all the images captured to determine whether stroke and roll are in fact correlated to the number of cycles, as these results may indicate. Additionally, further investigation into the amount of damage caused to actual kiwifruit, because of slippage, can be done to fully quantify this performance attribute of the end-effectors.

5 Improvements

The design of the imitation kiwifruit assembly was such that the sample would, whilst undergoing testing, grasp a geometrically mean kiwifruit. Nevertheless, the PLA imitation kiwifruit sections remain an imperfect representation of an actual mean kiwifruit with regards to surface texture and elastic modulus. The PLA sections' surface is more slippery compared to either a green or gold kiwifruit skin. This however is not entirely dispositive. It can be argued that the end-effectors will perform better in the field than the presented slippage results suggest, as there is less of a tendency for slippage to occur with real kiwifruit. Nevertheless, to improve the accuracy of the fatigue test's slippage results, the imitation kiwifruit sections' surface should be made from a material whose surface coefficient of friction (against Resione F80 elastic resin) is closer to that of the surface of a mean kiwifruit.

Kiwifruit are harvested long before they are ripe and are thus relatively hard when they are collected. Still, because kiwifruit are constituted by organic matter, one would expect the elastic modulus of a harvest-ready kiwifruit to be less than that of the solid infill imitation kiwifruit sections used in PneuGrip 2. The entire imitation kiwifruit assembly is not designed to elastically deform (as an actual kiwifruit might) when grasped. This fact reveals an inaccuracy in the results for the gripper finger output forces (Fig 12), and the observed wear on the end-effectors (Fig 10B). Whereby an actual kiwifruit would result in lesser gripper finger output forces, and less total wear on the end effectors. Work should therefore be done to experimentally test and determine the elastic modulus of a mean harvest-ready kiwifruit. The findings of which can be used to select a material to replace the PLA imitation kiwifruit sections, and/or inform a design change of the imitation kiwifruit assembly to produce a reaction more similarly to how an actual kiwifruit elastically deforms when grasped.

Due to time constraints, only a single fatigue test of a single sample has been conducted using PneuGrip 2 thus far. Therefore, from a statistical viewpoint, the load cell results presented in this paper are not significant. Certainly, to address this limitation, work should be done to determine the number of samples required to yield statistically significant fatigue testing results.

6 Conclusions

This paper outlined the mechatronic design of PneuGrip 2 and discussed the results of a one million cycle fatigue test of a compliant mechanism gripper-end effector sample. After the test, the gripper was completely intact. The K2 side end-effector catastrophically failed, whereas the K3 side end-effector experienced lighter surface wear. Over the course of testing, there was no significant degradation observed in the finger force outputs and Actuator G input force. The gripper produced a sufficient FDF for a total of 962,252 cycles. Irregular air pressure distribution is a speculated cause for non-uniform fluctuations observed in load cell data plots. Slippage appears to worsen with the increasing magnitude of stroke and roll parameters from the first to last test cycle. Improvements include changing the design of the imitation kiwifruit assembly to be more representative of an actual kiwifruit and completing multiple fatigue tests to bolster the statistical significance of results associated with functional performance.

Acknowledgement

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