University of Southern Queensland
Faculty of Health, Engineering and Science

Low-cost Firmness Based Avocado Ripeness Tester

A dissertation submitted by

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Towards the degree of

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Abstract

Approximately 7.3 million tonnes of food is wasted annually in Australia. A substantial portion of this food is discarded due to having expired before being consumed. Measuring the ripeness of fruit and vegetables can assist with managing fresh produce to limit food wastage. Most current ripness sensing methods are expensive, time consuming or destructive. A gap exists in current methods for a low cost, non-destructive device capable of measuring ripeness.

This project aimed to address this knowledge gap by constructing and testing a low-cost firmness based non-destructive ripeness measuring device. The device was constructed and tested against an judgement made by a human panel. Results showed a correlation between the human judgement and the judgement made by the machine. Further testing is required to determine if the method used correlates to current methods of testing for ripeness and whether factors such as fruit size, fruit shape, and temperature have an impact on the results achieved.

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I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Jared Mathews

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Acknowledgments

To my supervisor, Dr. Craig Lobsey, for his patience, assistance and expertise throughout this project.

To the university staff who have gone above and beyond to contribute to my learning while at USQ.

And to the friends who have been with me throughout my journey, the highs and the lows

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1. Introduction

Food waste is a major problem facing society as a whole. As the population rises managing limited global resources to feed the population will become a more and more significant challenge. A major component of food waste comes from food that is left to go off before it is consumed.

Ripeness testing is a potential partial solution to food wastage by acting as a tool to estimate the expected shelf life of fruit and vegetables. There is a gap in the currently available methods for testing ripeness. Current ripeness testing methods are typically expensive, time consuming, destructive or provide a poor indication of ripeness.

This investigation serves to improve on the methods available to test ripeness of fruit, in particular, avocados. A low cost machine capable of measuring firmness of a fruit or vegetable will be developed and tested against a panel of human assessors. The machine will utilise a stepper motor to provide precise linear control of a press which will include a load cell to measure the force applied at different levels of compression.

1.1 Objectives

The main objectives of the project are as follows:

- Determine if stiffness testing can measure the ripeness of fruit
- Develop a low-cost and automated device that can provide an objective assessment of fruit ripeness without damaging the fruit

Determining if stiffness testing is a viable means of ripeness testing is the primary objective of the project and further objectives will be pursued after the successful completion of the first objective. This objective includes determining if stiffness testing has any viability at all and determining the accuracy of the assessment.

Assessing fruit ripeness through destructive testing is a well-established method of testing fruit ripeness. One of the main and obvious drawbacks of this system is the destruction of the fruit. Fruit that has been tested destructively must be discarded or served immediately and may not be suited to certain dishes after testing. Additionally, if the fruit is found to not be ripe yet the fruit is wasted as it would be unfit for serving immediately and will not have the opportunity to ripen further. Even if only a sample of the fruit is tested to estimate the stage of maturity of a much larger crop, the destructive testing would represent a non-negligible percentage loss of a crop though the life and distribution of the crop.

1.2 Expected Outcomes

The machine developed and used in the investigation will be constructed in such a way as to gain a degree of precision from relatively low cost components. Current firmness based ripeness testing is typically conducted in a destructive manner. This investigation hopes to determine if non-destructive firmness based testing can be used as a manner of assessing avocados or fruit in general for ripeness.

The expected outcomes of the project are as follows:

- A prototype non-destructive firmness based avocado ripeness testing device.
- Data from a trial sample of avocados assessed by a panel of humans and the testing machine
- Considerations for the development of any similar future devices

2. Literature Review

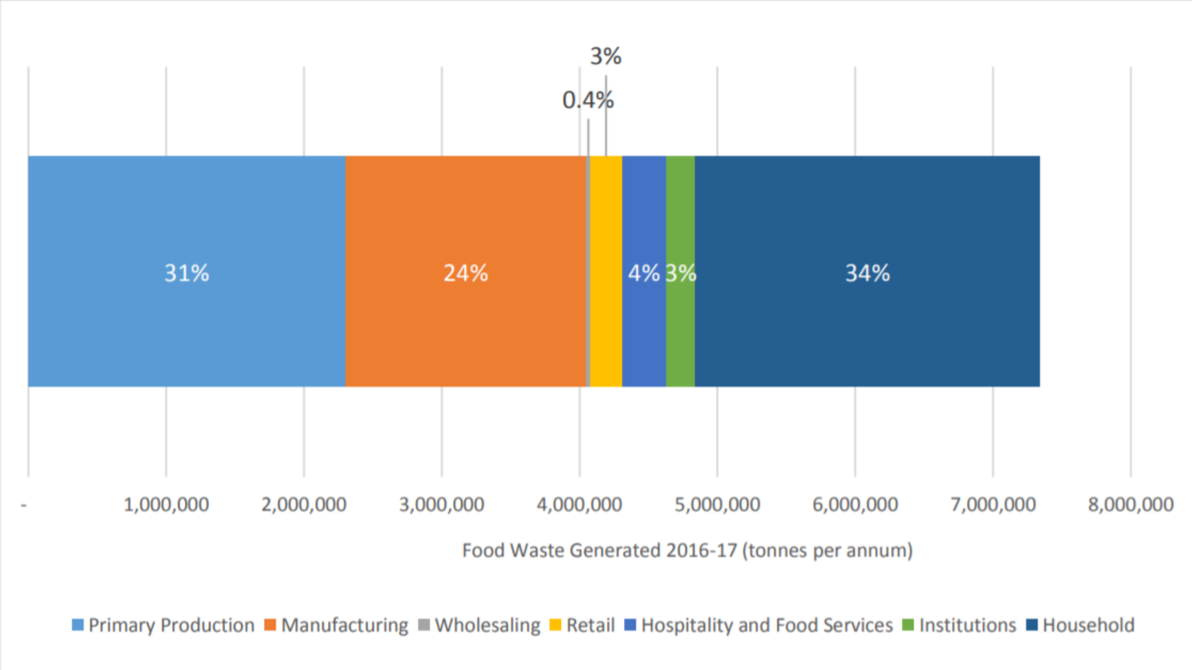
2.1 Food Wastage

In the 2016/2017 financial year Australia generated an estimated 7.3 million tonnes of total food waste. This waste occurs across multiple sectors. Waste is managed differently across sectors and where possible is used in other ways to minimise the overall loss experienced by the companies involved. These include composting and using the waste product as animal feed.

Some of the major factors contributing to food waste in fruit and vegetables occur on a large scale early in the production cycle and are difficult to control. These include on-farm damage, market forces, cosmetic standards, perishability and processing and transport losses. 422,000 tonnes of fruit and vegetables were lost at pack houses, most of which was composted and a further 840,000 tonnes were lost during processing, which was mostly repurposed as animal feed.

Nearly 53% of the 26,300 tonnes of food wastage in the wholesaling sector, consisted of fruit and vegetable waste. This waste was sent to compost. The hospitality and food services sector identified “Damaged or spoiled food due to improper food transportation or storage” and “Neglected / unprepared food and ingredients past their use-by date”. While the sector contributes a small percentage of food waste, it is a considerable portion and has some of the more easily addressable contributing factors.

The largest contributor to food waste is the household sector, contributing 2,500,000 tonnes of waste. The major contributor to household food waste is expired, unconsumed food. Most of this waste is disposed of through garbage collection services while some may be composted, disposed of in a worm farms, or disposed of through the sewage system.



It can be reasonably seen that food wastage is a significant issue. One of the contributing factors to food wastage is food expiring at various stages of the production cycle. The major contributor to the most wasteful sector is food expiring before it is consumed. It can therefore be deduced that difficulty in gauging the expected lifespan or ripeness of foods.

2.2 Ripeness Testing

Brezmes Et al. (2005) provided a summary of various common ripeness testing methods in their paper titled "Evaluation of an Electronic Nose to Assess Fruit Ripeness"

Ripeness itself is difficult to define, let alone quantify, due to there being no single characteristic that directly correlates to the perceived fruit maturity or ripeness. Ripeness is therefore a perception rather an objectifiable quantity. This of course make the process of gauging fruit or vegetable ripeness difficult.

In lieu of a single method of measuring "quality indicators" are typically used to assess fruit maturity. Common quality indicators used to assess for fruit ripeness are: firmness, colorimetry, soluble solids content and titratable acidity, starch index and vapour production. Each of the methods have certain drawback that limit their effectiveness.

2.2.1 Laboratory Methods

To provide an objective assessment of ripeness a number of laboratory methods exist, however these are typically invasive or destructive.

Firmness has a high correlation to ripeness and is easy, fast and cheap to test. Firmness testing is typically carried out using a penetrometer which penetrates the skin or surface of the fruit and measures the required force. This makes firmness testing a favourable ripeness rest and is commonly used but is a destructive test. This limits the number fruit that can be tested in a batch as any tested fruit cannot be sold on as whole fruit. This also limits the capacity for testing throughout the life of the fruit.

Soluble solids and titratable acid testing require the destruction of the fruit to test them. The testing process for these quality indicators is also quite involved and time consuming.

Starch index testing is conducted by staining a section of the fruit and visually assessing the colour an a scale from 1 to 6. Starch index testing is inexpensive but time consuming and has low correlation to ripeness. The testing also leaves a stain on the fruit which can be off putting to consumers.

2.2.2 Sensor Based Methods

A number of sensor based methods have been proposed.

Colorimetry is a fast and non-destructive method of assessing fruit. Parameters such as hue and saturation are often assessed. The main drawbacks for colorimetry testing are the expensive instrument used and the fact the colorimetry does not correlate well with ripeness for some species of fruit.

Vapour production typically tests for ethylene which is a good indicator of ripeness as the presence of ethylene activates the ripening process. Ethylene testing is conducted by placing the fruit in respiration jars and taking samples from the air. provides a relatively good indication but is time consuming and requires specialist equipment

The study went on to test the electronic nose that was the subject of their investigation and found good correlation to traditional quality indicators.

Galili et al. (1998) used an acoustic device to gauge the ripeness of avocados. A mechanical impulse was delivered to the avocados and the amplitude and frequencies of the resulting sound was recorded. Destructive Magness-Taylor probe tests were also carried out on the avocados to establish the correlation between destructive and non-destructive testing. The paper also stated that mechanical properties of fruit are “good indicators of their maturity, degree of ripeness, and predicted shelf-life”. The experiment found a correlation between the acoustic testing and destructive testing and found that the first resonant frequency of the fruit had a higher correlation to the destructive testing than the frequency of maximum amplitude. The experiment also found that the position the mechanical impulse was applied and the corresponding position the response was measured had a significant impact on the frequency response.

2.3 Knowledge Gap

There is a gap in current literature and practice for a quick, low cost non-destructive ripeness tester. This project aims to address that gap.

3. Methodology

3.1 Project Methodology

In Completing the project, a number of general stages were completed. The stages and an outline of each are as follows:

- Literature review: A literature review of the existing methods of assessing fruit for ripeness and potential new solutions including sensing devices and equipment

- Design of ripeness testing device and sourcing of parts: after envisioning a general testing device design, parts and materials were then sourced and custom parts designed and manufactured to fit the purchased equipment

- Construction of the testing device: this included the assembly of all mechanical parts, and wiring of electronic components

- Writing of device code: this stage saw the development of the code used to control the testing device and collect the data

- Data collection: utilising a panel of people to assess the ripeness of the avocado samples and using the testing device to collect data.

3.2 Testing Methodology

3.2.1 Samples

A sample of fruit will be chosen to provide a range of fruit from under ripe to over ripe. The proposed sample size is ten fruit but may be increased if the experiment does not yield useful data with a sample of ten.

3.2.2Human Assessment

To evaluate the effectiveness of the testing machine, a human assessment was be performed. The objective of the human assessment is to establish a bench mark with which to compare the assessments made by the machine. The end goal of the project is to create a machine which can assess ripeness relative to what humans perceive as ripe. As ripeness or readiness for consumption is judged by the humans who eat them, it is most suitable to use humans to evaluate the ripeness of the fruit rather than another scientific method such as acoustic testing or electronic nose (gas) testing.

A panel of eight people familiar with the fruit were chosen to evaluate the ripeness of the fruit. The sample of fruit will be randomly labelled a, b, c, d and so on and the panel will be asked to judge the fruit and rank them in order from most underripe to most overripe and assess which of the fruit is most ready for consumption. Each of the assessments from the panel members will be made as close together as possible in order to minimise change in ripeness over the duration of the assessments. The time and order of the assessments will be noted to account for any change in ripeness or perceived ripeness caused by change in time or contact with the panel members. Ideally the most ready fruit will be somewhere in the middle of the sample, (not at either end) so that there are examples of underripe and overripe fruit present.

3.2.3 Equipment and Data Collection

The testing will require the use of a specialised testing equipment, purpose built for testing the firmness of fruit. The rig will consist of a vertical press actuated by a drive screw and a stepper motor. The lead screw and stepper motor configuration will allow for accurate control of the linear position of the vice. Attached to one surface of the vice will be a force sensor to measure how much force is being applied to the fruit. This test equipment will also act as a prototype for any commercial product that may arise from this investigation. The test procedure is implemented largely by the program running on the micro controller. The overall procedure will be:

1. Place a fruit in the test equipment

2. Commence test procedure

3. Remove fruit from test equipment

The test procedure executed by the test equipment microcontroller will be:

1. Wait for a button press
2. Begin lowering the force sensor
3. Wait for the force sensor to contact the fruit
4. Lower the force sensor a further known distance (0.5mm to 2mm)
   4.1. Record the force applied to the fruit after each step of the motor distances (i.e. every 0.1mm)
5. Maintaining the same position, continue to measure the force applied for a short time
6. Return the test equipment to original (fully open) position

After testing the fruit using the test equipment the fruit will be ranked in terms of stiffness. It is proposed that the stiffness of the fruit corelates to the ripeness of the fruit and as such it is expected that the ranking in stiffness from the test equipment will match the ranking in ripeness as determined by the panel.

3.3 Experiment Design

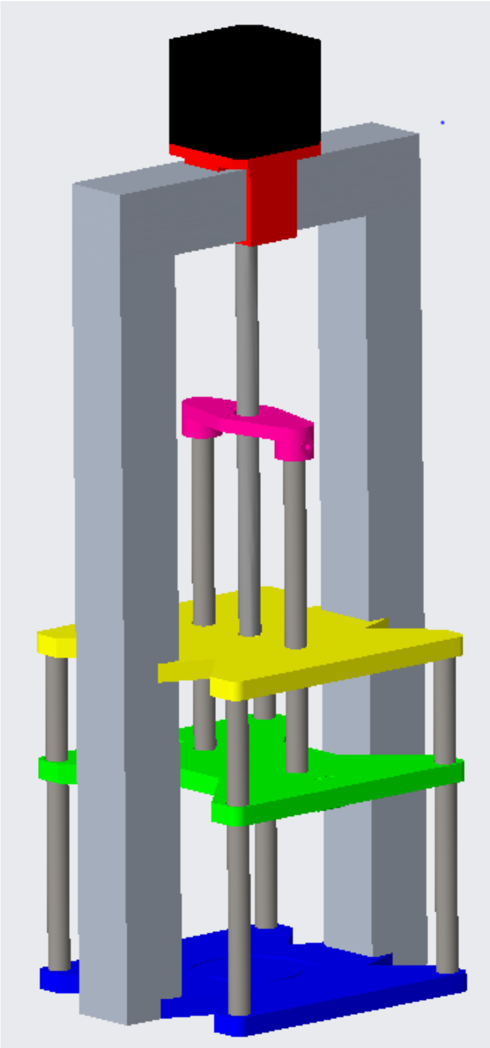
3.3.1 Hardware

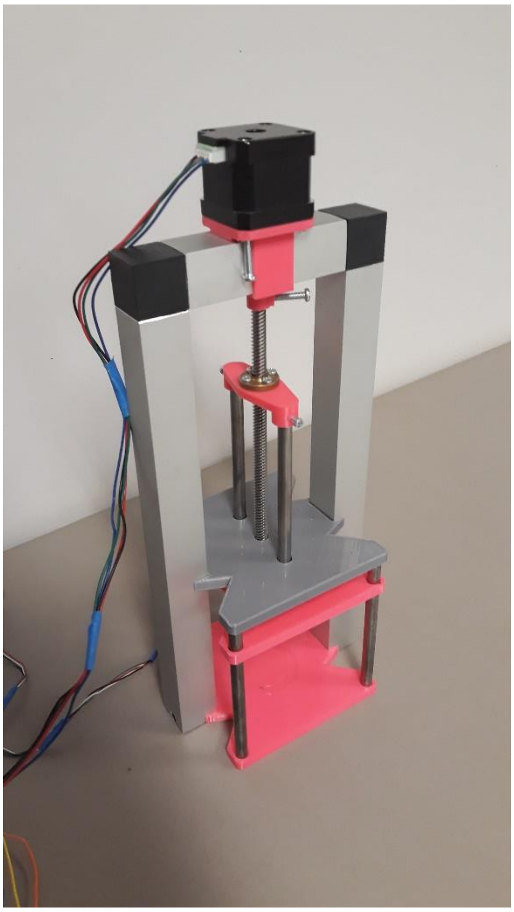
The testing device consists of several major components as well as components used to interface between the major components. The major components consist of:

- A 42SHDC3025-24B "Nema 17" type stepper motor
- Arduino Nano (ATmega328P)
- A 5 kg load cell (TAL220B)
- The test frame and associated parts

The interfacing components are:

- An HX711 load cell amplifier
- An L298n motor driver board





3.3.2 Hardware Justification

The Nema 17 stepper motor was chosen due to the ease of control, precision available, torque capacity, standard size, local availability and relative low cost. The Nema 17 is a bi-polar stepper motor with 200 steps per revolution (1.8° steps).

The Arduino nano was chosen due mainly for the low cost and ease of programming. The code used to run the test is relatively simple and fits well within the memory capability of the ATmega328P microcontroller. The Arduino nano also has more than enough available pins to receive the required input and provide the signals to control the stepper motor. The pinned design of the Arduino Nano also allows for easier use with a prototyping breadboard. A single push button was connected to the Arduino to allow the testing to be manually initiated.

The 5 kg load cell has four integrated strain gauges connected in a wheatstone bridge configuration and is useful for loads up to 5 kg. The 5 kg model was chosen over a smaller more sensitive model due to the wide range of forces measurable allowing for testing of more rigid fruit or vegetables while also maintaining a fairly high sensitivity to forces. The load cell also features tapped holes for easy mounting.

The test frame was designed and constructed specifically to house the above components and allow testing to take place. The frame was constructed from the following parts:

- 26 x 26mm aluminium square hollow section
- Right angle joiners (Aluminium section)
- 8mm steel rod
- Drive screw and nut
- 3d printed PLA base
- 3d printed PLA press
- 3d printed PLA guide
- 3d printed PLA stepper motor mount
- 3d printed PLA press head
- 3d printed PLA push rod connector
- 3d printed PLA coupler (motor shaft to drive screw)
- Various screws used to connect pieces

The frame was designed to fit a typical avocado within the test space with some spare space to allow for larger species of fruit if desired at a later stage. Where possible, "off the shelf" materials were used however these materials were required to be cut to length. Specialised parts that were not commonly available were 3d modelled and printed using PLA filament in order to allow for fast, low cost prototyping and manufacture with finer tolerances than would be practical with hand tooling. The assembly was designed in such a way as to allow for disassembly of the device if required, particularly to replace a component with an updated version.

The heavy reliance on 3d printing was effective for developing a prototype however a more time effective manufacturing method should be implemented if any significant quantity of the devices were to be manufactured.

The HX711 load cell amplifier allowed for precise and accurate measurement of the forces applied to the load cell. Several libraries have been written for the HX711 which made for easy integration into the test apparatus.

The L298n H bridge motor driver board allowed for the required voltage and current to drive the stepper motor. The Arduino nano is not capable of providing enough current by itself so a driver is important.

3.3.3 Code

The code used allows for setup to be completed and testing started with the use for a single button. Upon start up, the device will wait for the button to be pressed and then locate the bottom of the range of movement using the load cell. The press will then move to a known position at the top of the range of movement allowing for the fruit diameter to be measured by the machine.

After locating itself, the machine will then wait for a button press again. Once pressed, testing commences. The machine lowers until something is detected by the load cell. Once detected the machine then lowers a further 2mm, taking a force reading after each step of the machine. Once 2mm has been reached, the machine will stop in place and wait for 6 seconds while continuing to take force readings. Once this is complete the machine resets ready for the next test.

While in the current prototype stage, output is printed to the serial monitor of a connected computer where it can be copied for analysis. A commercial version of the machine would have an integrated data logger and storage capacity as well as real time assessment of ripeness.

3.3.4Calibration

Prior to conducting any testing the load cell required calibration. This was performed by removing the press assembly from the machine and inverting it to use as a scale before placing a known weights on the sensor and adjusting a calibration factor so that the Arduino would output a result that reflected the known weight

3.4 Safety Issues/ Risk Analysis and Ethics

In any project there are some inherent dangers. Although this project is quite low risk it is important to address any potential safety issues to ensure the project is as safe as possible. The main hazards in this project are the use of electricity and moving parts which have the respective risks of electric shock and pinching/crushing injuries. These risks are addressed in the Risk assessment table below in appendix D.

As this project makes use of humans undertaking a kind of survey, ethical considerations must be considered. Some of the ethical considerations are outlined below.

- No personal information is collected
- Participants have the use for the testing explained to them
- Participants are asked to undertake a simple task with minimal associated stress
- Participants participate voluntarily and are free to leave at any time

A formal ethics statement is located at appendix E

4. Results and Discussion

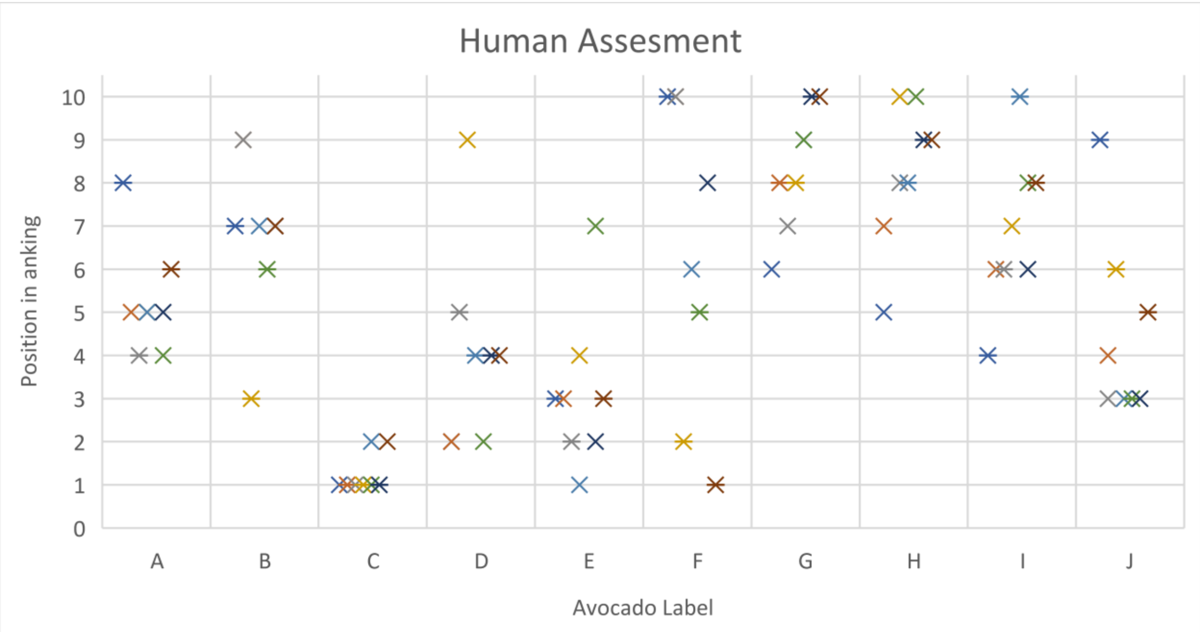
The main objectives of the project were to:

- Determine if stiffness testing can measure the ripeness of fruit
- Develop a low-cost and automated device that can provide an objective assessment of fruit ripeness without damaging the fruit

The device was successfully constructed and testing performed on a sample of 10 avocados with a panel of 8 people. The results indicated a correlation between the conclusions drawn from human testing and the testing performed with the use of the testing machine.

4.1 Human Assessment

Each person on the panel judged the avocados and their assessments were recorded. Refer to figure (human assessment) for the results of the human assessments. The full table including the complete assessment of each panel member can be found in appendix F.



The inconsistency of human judging becomes immediately apparent after viewing the results from the human judging. Avocado F was judged to be both the most ripe and also the least ripe avocado of the group by different judges. Avocado D saw a similar variation in judging, being judged both the second ripest and second least ripe by different judges. Avocado C on the other hand was judged to be either the least ripe or second lest ripe by all 8 judges. All other fruit had a range of at least 5 positions.

Different assessment criteria were implemented by different judges with some using firmness as a sole indicator Where others used colour as the primary and some used a combination. Despite efforts to conduct all testing as close together as possible there was a noticeable decline in the condition of the fruit from the beginning of judging to the last judge, most noticeable was a softer, less crisp feeling skin at the end of testing.

Avocado F was remarked by several of the judges to be "off-putting" due to the greener appearance of the avocado skin but also particularly soft regions of the avocado closer to the stem area. It should also be noted that although avocado F was purchased from the same section of the same store, avocado F was produce of New Zealand rather that Australia like the rest of the samples and was likely subject to different growing, harvesting, storage and transport conditions to the other samples.

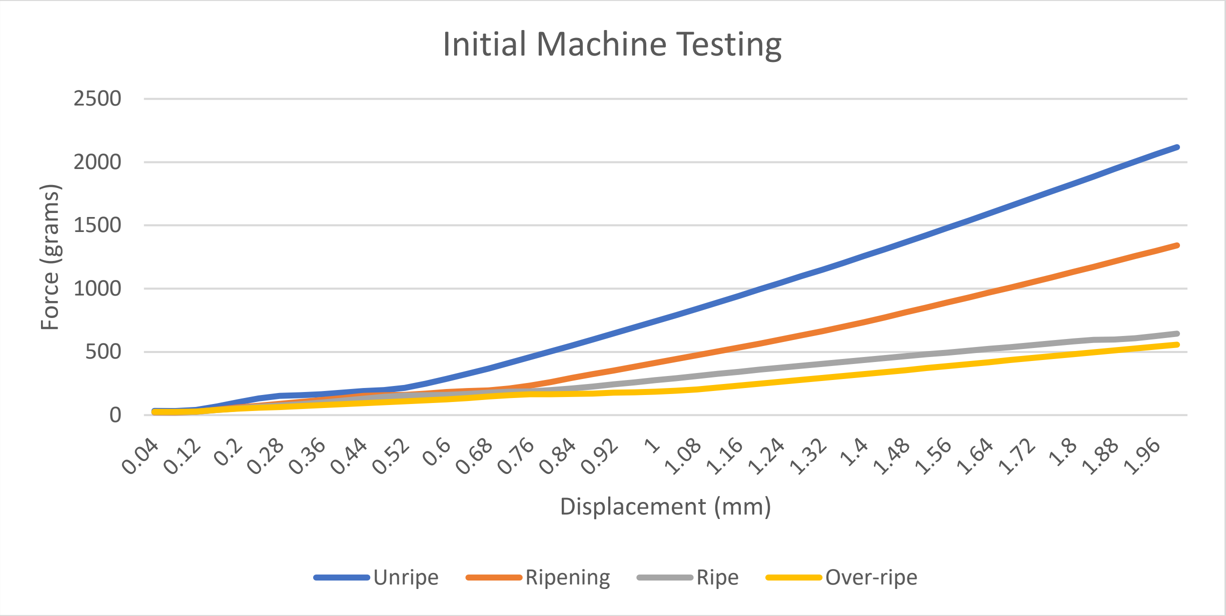
Judge number 2 commented that while it was they were confident that the 5 least ripe avocados wer the 5 least ripe, it was difficult to determine the relative ripeness within the group of 5. This suggested that untrained humans can reasonably distinguish between ripe and unripe avocados, the difference within general groups of ripeness is difficult to define.

The position of the avocado within each of judges assessments was recorded as a ranking and the ranks from each judge were averaged to form a collective "human" assessment for use when comparing the human testing results to the machine tests.

4.2 Machine Testing

4.2.1 Initial Testing

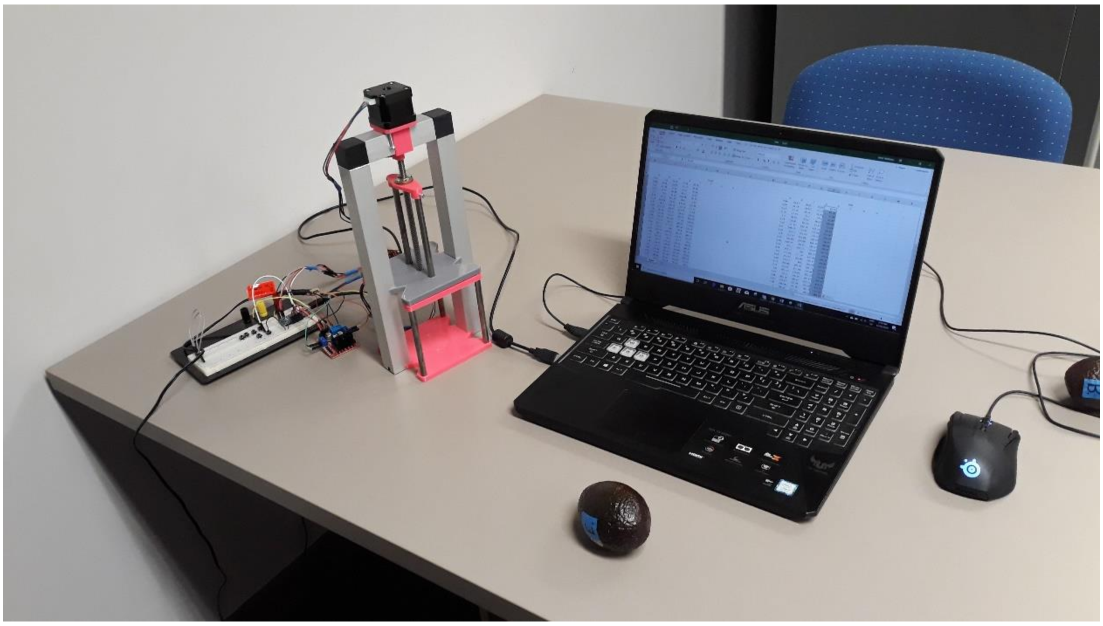
An initial test was performed using a only 4 avocados which where quite distinguishable from each other due to their state of maturity. This testing was conducted to identify any potential issues with testing and to test for viability of the project. The initial testing resulted in increase in the delay between steps of the motor and an added "settling time" stage to the test procedure. The data collected from these tests is located in appendix G. The results are shown in figure ().

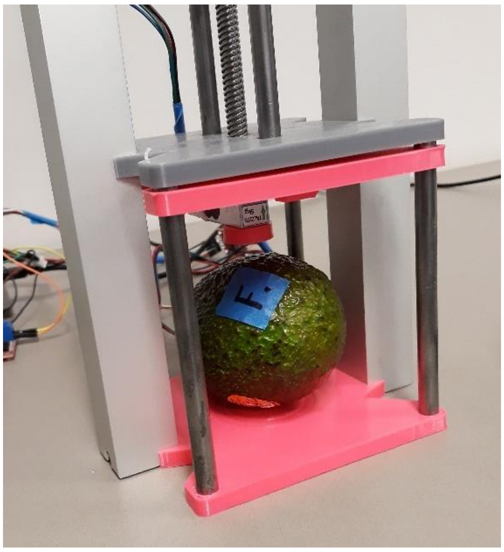


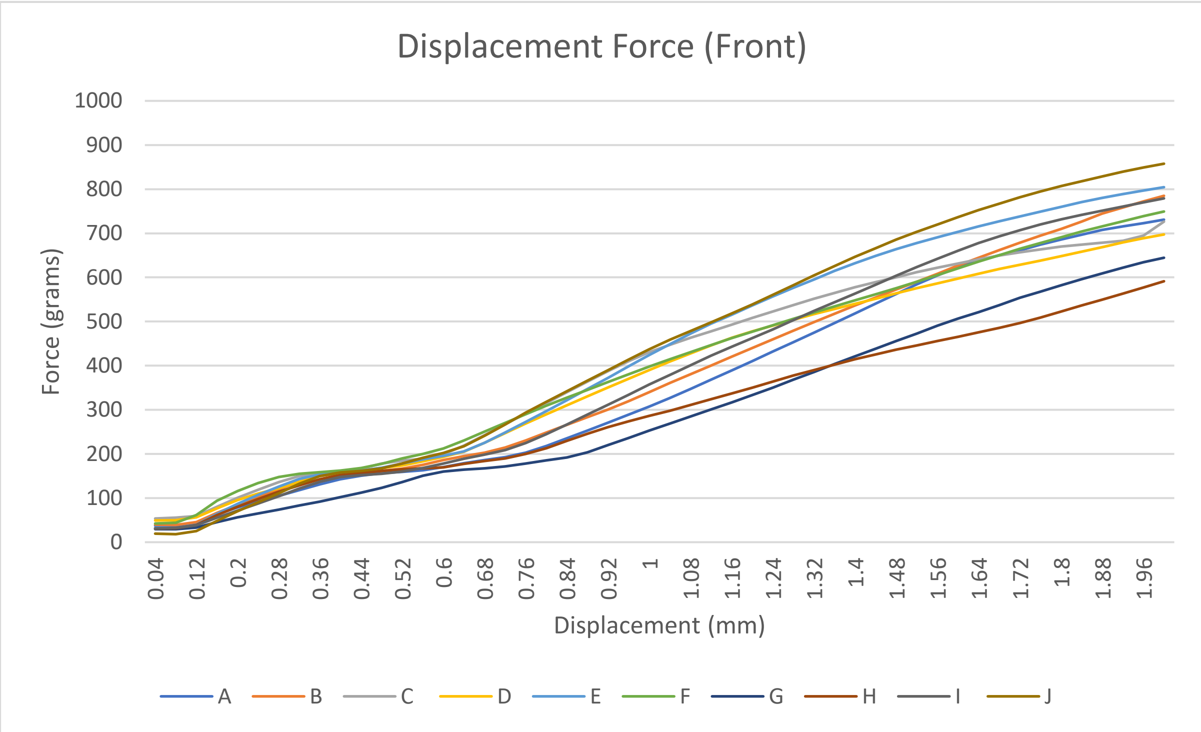
The initial testing showed a clear distinction between the different fruit samples based on the force response to an applied displacement. A distinction between the fruit can easily be made at the 1 mm displacement mark with a very clear distinction between the samples at 2mm. This testing demonstrated the viability of the experiment and identified where an improvement to the machine design could be made to remove play from the motor to drive screw coupling and improve the quality of data. This improvement was made to the machine before re-running the tests and collecting the results shown in figure (). Additionally a small amount of play between the drive screw thread and the drive screw nut was discovered but did not appear to significantly affect the data collected and was thus left alone.

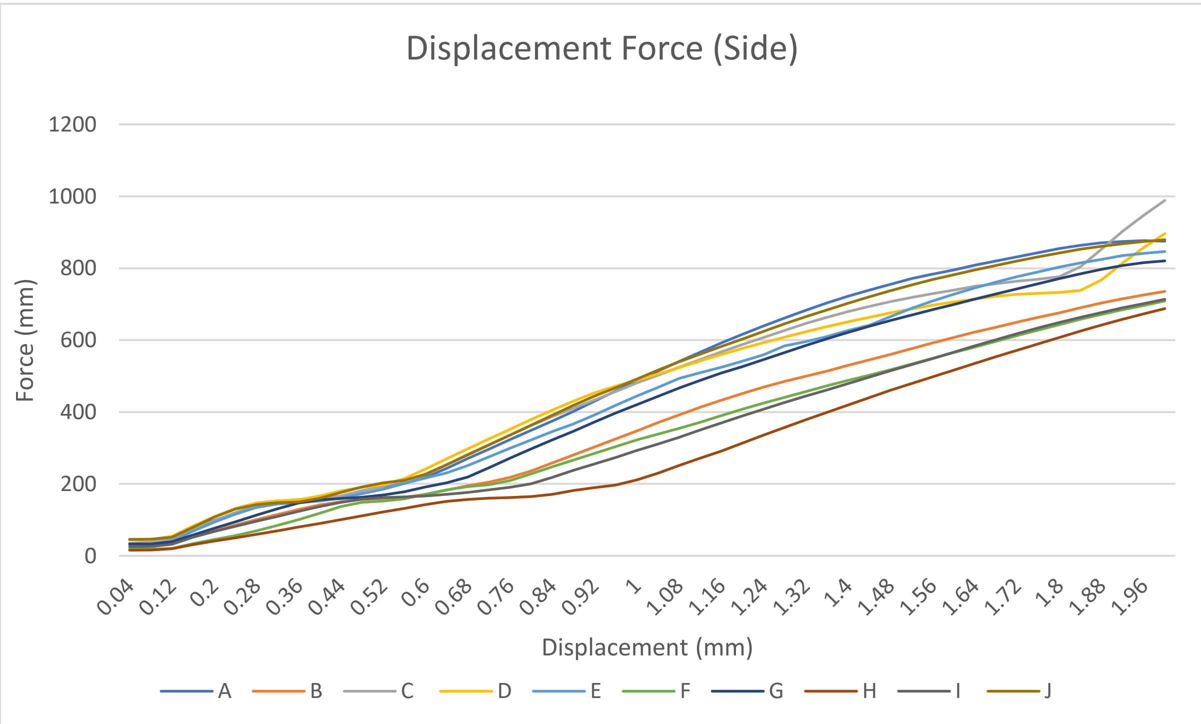
4.2.2 Testing

For final testing, each fruit was tested once with force being applied to the front of the fruit and once with the force being applied to the side of the fruit. Two sets of data were collected from each test; the displacement force data and the settling time data. Tables containing the full sets of data can be found in appendix H. Graphs of the data can be seen in figure (), (), () and ().





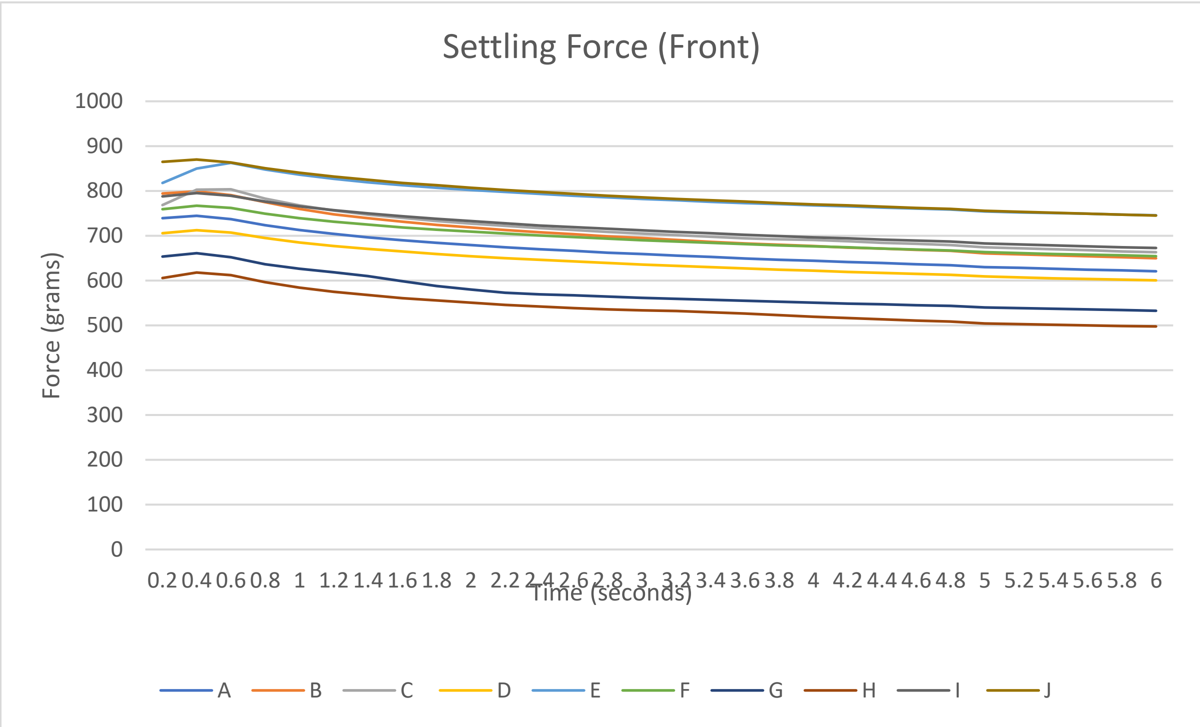

Displacement Force (Front)
Force (grams)
0
100
200
300
400
500
600
700
800
900
1000
0.04
0.12
0.2
0.28
0.36
0.44
0.52
0.6
0.68
0.76
0.84
0.92
1
1.08
1.16
1.24
1.32
1.4
1.48
1.56
1.64
1.72
1.8
1.88
1.96
Displacement (mm)
A
B
C
D
E
F
G
H
I
J

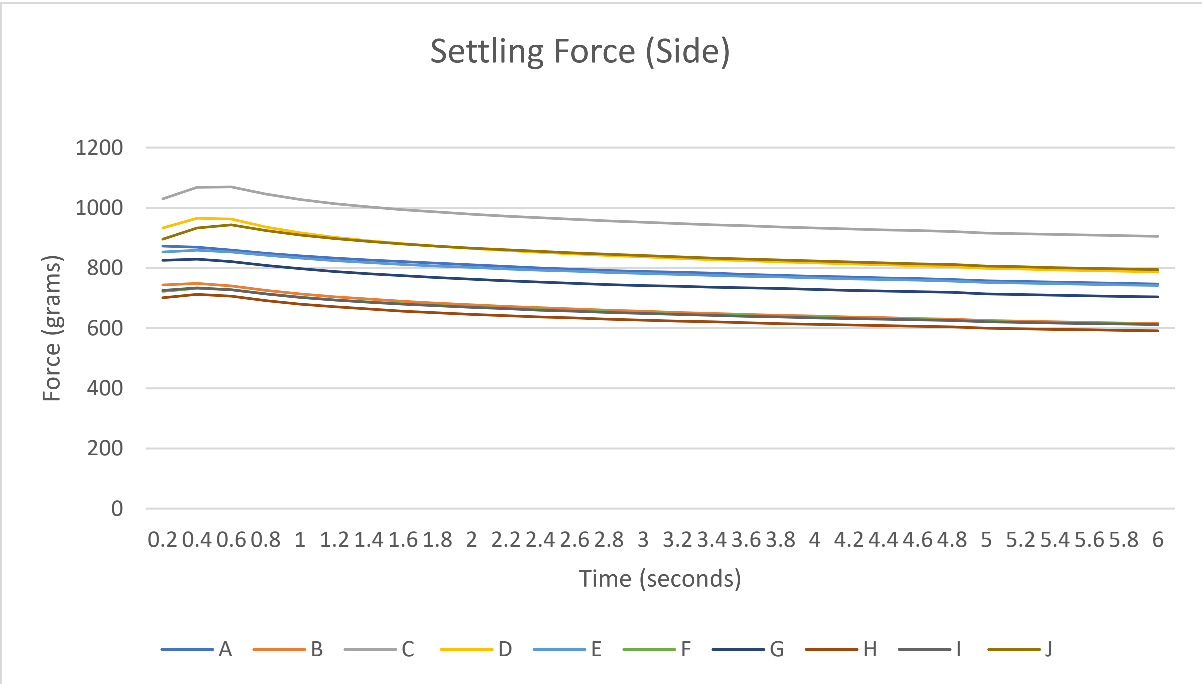

Displacement Force (Side)
Force (mm)
0
200
400
600
800
1000
1200
0.04
0.12
0.2
0.28
0.36
0.44
0.52
0.6
0.68
0.76
0.84
0.92
1
1.08
1.16
1.24
1.32
1.4
1.48
1.56
1.64
1.72
1.8
1.88
1.96
Displacement (mm)
A
B
C
D
E
F
G
H
I
J

It can be seen in figure () and () that the curve for every avocado tested converges at around 150 to 170 grams before diverging again. It is believed that this is the result of play between the drive screw and the drive screw nut. Before 150 grams the press part of the testing device is “hanging” from the drive screw. After contacting the fruit, weight is transferred from the drive screw to the fruit until approximately 150 grams is reached. At this point all of the weight of the press assembly supported by the fruit and further rotating the drive screw does not impart any additional force until the thread on the drive screw begins to push the press down again. While curve sits in the region between 150 and 170 grams, the press is not displaced any further. This results in an error in the displacement equal to the linear play between the drive screw and nut, in this case approximately 0.15mm. This means that the values displayed along the x-axis are not a true displacement value but has been left this way because displacement is more significant to the experiment than possible alternate x-axis labels such as motor steps because displacement is a function of the step angle of the motor, and the thread pitch which may vary between test devices.

Reffering to figure (), () and (), it can be seen that the curves follow a different trajectory between the intial testing and the final testing. It is believed that this is the result of an increased time delay between motor steps from initial testing to final testing. The delay between steps was increased from a nominal value of 10 milliseconds to 50 milliseconds to allow the fruit to settle between compressions and provide a more accurate result.

It can also be seen that curves for different avocados cross over on several occasions which was unexpected after the results shown in figure(). With a limited sample size it is difficult to determine the cause of the changes in trajectory. Possible causes include inconsistencies in the fruit skin or flesh such as damage or varying shape and size, as well as movement that may have occurred during the testing process. This is significant as the trajectories crossing mean that if the result was taken at different points in the testing, a different assessment would be made of the fruit. It should be noted that avocado C and D which showed among the most erratic behaviour were also judged to be relatively unripe compared to the rest of the sample. It is possible that this kind of curve is indicative of an unripe avocado.


Settling Force (Front)
Force (grams)
1000
900
800
700
600
500
400
300
200
100
0
0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3 3.2 3.4 3.6 3.8 4 4.2 4.4 4.6 4.8 5 5.2 5.4 5.6 5.8 6
Time (seconds)
A B C D E F G H I J


Settling Force (Side)
Force (grams)
1200
1000
800
600
400
200
0
0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6 2.8 3 3.2 3.4 3.6 3.8 4 4.2 4.4 4.6 4.8 5 5.2 5.4 5.6 5.8 6
Time (seconds)
A B C D E F G H I J

The settling force curves for each avocado shown in figure () and () are virtually parallel for the entire dataset, with the exception of the first second. This may be an indication that data collected while displacement remains constant is a better indicator of ripeness, given that the displacement is applied correctly. That results in figure () show a very close correlation between the data from the force applied and the settling data for each style of testing.

Of interest is the fact that the force applied continues to rise for up to 0.6 seconds after increases to displacement have stopped. At this stage it is unclear what may be the cause of this but probable causes include settling within the machine and a delay in the force response of the fruit itself.

As there were no stand out areas of significance in the machine testing graphs it was decide that the last values recorded for each dataset would be used for data comparison.

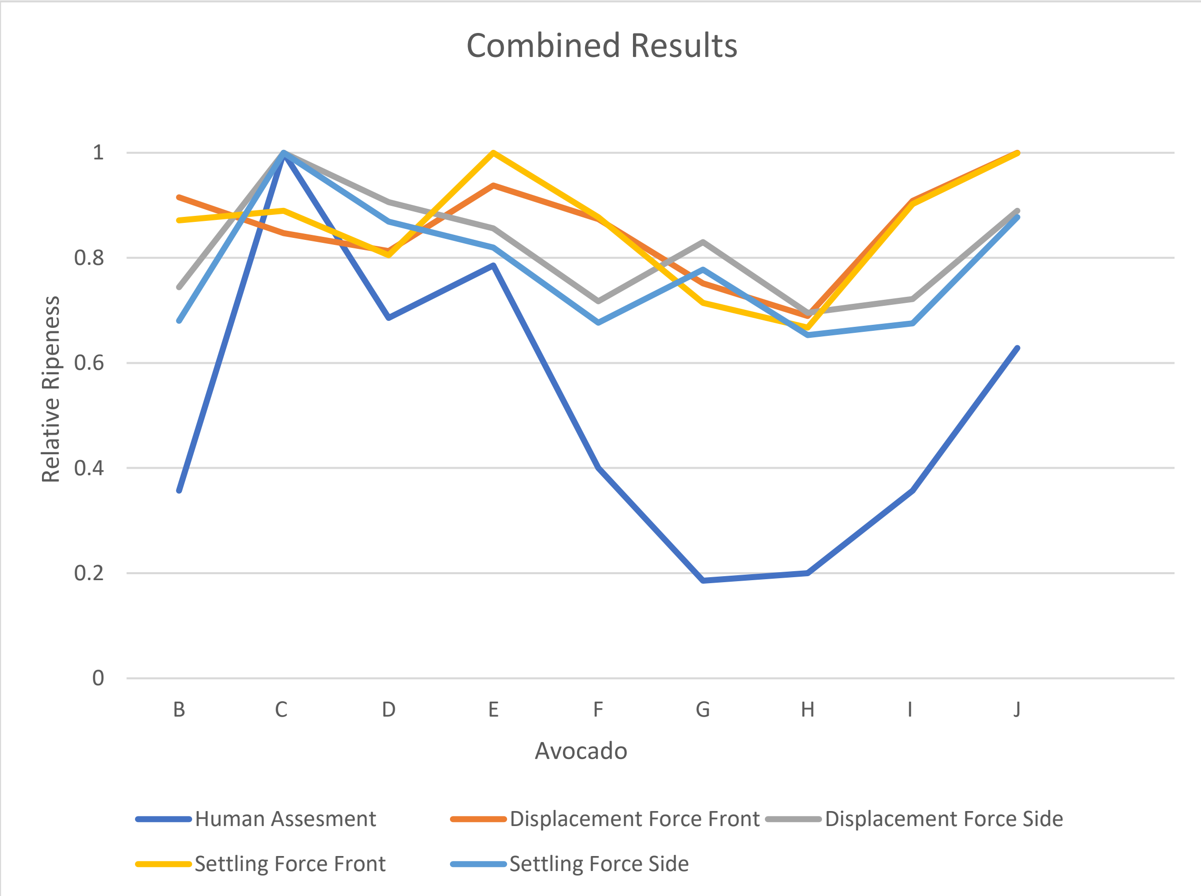
4.3 Comparisons

In order to compare the data collected from the different fruit testing methods, some manipulation of the data was undertaken. The scales used in the different tests work in opposite directions. High values in the human testing correlate with high ripeness whereas low values in the machine testing correlate with high ripeness. The different tests also used very different scales due to the difference in nature between the tests.

To correct the data non compatibility, the averages from the human testing were subtracted from the maximum value of 10 in order to invert the scale. Secondly to correct the difference between the scales. Each value was divided by the highest value within its dataset to get the value as a percent of the highest recorded value. While this ensured that the values would be within the same range, the different natures of the testing mean that the percentages would likely be expressed differently. The human testing required that the avocados be scored from 1 to 10, thus enforcing an artificial scale whereas there was no such artificial scale for the machine testing and values were simply as they were recorded. This has resulted in a much more even distribution among the available ranges for the human testing data. The final scale used in figure () is between 0 and 1 with lower values corresponding to riper fruit

Despite the differences in scale, the results in figure () show a correlation between the data from human testing and the data from the machine testing. The data from the front force testing has a higher correlation to the human data than the side force testing. It is unclear what the reason for this is at this stage and further testing would be required to determine if this is consistent or purely coincidental in this case.

These results show that non destructive firmness based testing is able to provide an indication of fruit ripeness to a similar accuracy to a human.



4.4 Discussion Summary and Weaknesses

The testing was able to demonstrate a correlation between ripeness as judged by humans and ripeness as judged by the test machine. The main weakness to the testing was the limited sample size and baseline establishment. Although the average values of the human judging correlated to the machine assessment, there was significant variation between each judge. In order to establish a stronger baseline a panel consisting of more people would be required. The with a larger panel size however, is the deterioration in fruit between judges. Even with a small panel of 8 people, there was a noticeable difference between the condition at the beginning of testing and the condition at the end of testing. Increasing the panel size would likely worsen the condition of the fruit by the conclusion of judging,

The limited number of avocados tested also caused limitations to the conclusions that could be drawn and the justification of the results seen. For example the testing was unable to determine if the size of the fruit played a significant impact on the perceived ripeness as seen by the machine. It is also impossible to determine if the orientation of the fruit in testing was significant to the results.

5. Conclusions

This investigation showed promising results for the small sample size utilised. A testing device was successfully constructed and a correlation between testing device assessment and human judging was seen.

5.1 Further Work

To expand and verify the results found, further testing with a larger number of fruit should be undertaken. A larger sample size would allow for more insightful conclusions to be made. Additionally, a more solid baseline should be established in order to further compare the results from the testing to current industry practice. At the minimum, results from the use of a penetrometer should be compared to the results of non-destructive firmness testing as it is the most closely related ripeness testing method and most easily conducted testing.

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Appendix A

ENG4111/4112 Research Project

Project Specification

For: Jared Mathews

Title: Providing tactile feedback to a robot operator through low cost actuators

Major: Mechatronic

Supervisors: Craig Lobsey

Enrolment: ENG4111 – ONC S1 2019
ENG4112 – ONC S2 2019

Project Aim: Evaluate the effectiveness of a bi-lateral feedback system for operating robots and determine a suitable actuator and feedback model

Programme: **Version 2, 20/03/2019**

1. Investigate existing feedback systems for robot-operator teams
2. Review possible sensors and actuators for implementation in a force feedback system
3. Assemble a test device using appropriately determined components
4. Develop various feedback models for use with the test device
5. Develop a methodology and test apparatus to evaluate the bi-lateral feedback system for use on different objects or working conditions
6. Evaluate the effectiveness of feedback models with the selected sensor / actuator combination in providing tactile feedback to robot operators in a range of scenarios

If time and Resources allow:

7. Repeat tests with a different style of controller

Appendix B

Excerpt from Progress Report

Progress to date

The project has undergone a series of changes to get to where it currently is. The project was originally intended to be an evaluation of a unilateral vs bilateral feedback system for a human operator to control a robotic gripper. The goal of the original project was to provide a realistic feel of what the robotic gripper was experiencing to the user through tactile feedback to a user held controller in a general use, proof of concept type arrangement.

After receiving some feedback during initial presentations, the project was revised to focus more on accurately sensing the force experienced by the gripper. The revised project would look into overcoming the limitations of cheap force sensitive resistors and comparing their use to other force sensing methods including a load cell and current sensing of the motor supplying the force. It was also decided that a more specific area of application would need to be decided on.

When discussing a suitable area of application with the project supervisor, it became apparent that there had been limited work conducted on sensing stiffness. Fruit testing was suggested as a potential use of a stiffness measuring device with the focus on determining the ripeness of fruit. Initial investigation indicated that this was an area of study that had received limited attention in the past and made for a suitable project topic.

It should be noted that although the application for the project has drastically changed, the overall setup and general procedure have remained relatively similar. The project still utilises an actuator with linear motion and a force sensor. The actuator has been changed from a servomotor to a stepper motor to allow for greater positional control and the input from the sensors will be used in a different way but the concept remains very similar.

Appendix C

The timeline of the Project has been severely impacted by the alteration to the topic. This has resulted in the bulk of the project being completed in semester 2.

Phase	Week																																		
	Semester 1																Exams		Recess			Semester 2													
	Lead up	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
Old Project	■	■	■	■	■	■	■	■	■	■	■	■	■	■																					
Planning of new project														■	■	■																			
Resource gathering																			■	■	■														
Assembly of test equipment																						■	■	■											
Testing																									■	■									
Organisation of Results																									■	■	■	■	■	■	■	■			
Report finalisation																						■	■	■	■	■	■	■	■	■	■	■			

Appendix D

Risk Assesment

			Risk Assessment		
Hazard	**Risk**	**Controls**	**Consequence**	**Probabbility**	**Risk Level**
Electricity	Electric shock to people involved	Electricity being used is of low voltage not generally capable of causing injury, electricity source to be disconnected while live components are installed, contact with live wires and components to be avoided	Insignificant	Possible	LOW
Moving parts	Pinching/crushing injuries	Moving parts programmed to come to a stop with a safety gap to avoid crushing, potential pinch points built to allow body parts to become stuck, power disconnect in easy reach in event that a body part becomes stuck	Minor	Unlikely	LOW

Appendix E

Ethics Statement

In a project that has human involvement it is important to consider the ethical implications of the projects to ensure that none of the participants basic human rights are infringed on including but not limited the right to safety and the right to privacy. The human involvement in this project is limited to a small panel of people rating avocados in order from least ripe to most ripe.

It is the opinion of both my supervisor and I that this project falls into the following:

- projects that are not reporting on or publishing the results of the findings externally provided the nature of the research involves only minimal or negligible intrusion or risk to participants

- student projects with an education, training, or a practical experience focus do not normally require approval

As the project falls into the above categories and the project uses non-identifiable data with minimal intrusion or risk to the participants, no formal ethics approval is required.

Appendix F

Panel Assesment

	1	2	3	4	5	6	7	8	9	10
Person	least ripe									most ripe
1	C	D	E	I	H	G	B	A	J	F
2	C	D	E	J	A	I	H	G	B	F
3	C	E	J	A	D	I	G	H	B	F
4	C	F	B	E	A	J	I	G	D	H
5	E	C	J	D	A	F	B	H	G	I
6	C	D	J	A	F	B	E	I	G	H
7	C	E	J	D	A	I	B	F	H	G
8	F	C	E	D	J	A	B	I	H	G

Appendix G

Displacement	Unripe	Ripening	Ripe	Over-ripe
0.04	32.22	19.75	22.65	25.49
0.08	32.19	19.58	22.41	25.46
0.12	40.26	25.58	26.89	29.49
0.16	68.3	44.44	41.08	41.83
0.2	100.83	60.44	53.65	51.18
0.24	131.11	73.3	65.43	58.16
0.28	151.97	87.85	76.76	64.95
0.32	157.94	103.34	87.73	71.58
0.36	164.41	118.16	99.78	78.38
0.4	177.33	135.49	113.98	85.56
0.44	189.22	151.35	129.52	92.99
0.48	197.96	156.76	145.42	100.53
0.52	215.98	159.33	154.99	108.07
0.56	247.33	169.65	158.06	115.77
0.6	286.55	181.76	160.2	124.87
0.64	325.98	189.22	167.87	135.27
0.68	367.72	195.04	177.86	146.28
0.72	411.95	210.56	184.26	157.61
0.76	457.17	234.3	188.88	164.51
0.8	503.18	262.04	197.48	166.01
0.84	550.23	293.58	209.53	166.8
0.88	597.56	323.4	226.2	171.02
0.92	645.48	352.88	243.87	176.59
0.96	693.48	383.69	259.64	181
1	742.3	413.61	275.3	185.36
1.04	790.99	442.7	291.92	191.75
1.08	840.27	472.71	309.31	204.05
1.12	890.53	502.73	326.25	218.09
1.16	941.84	533.61	342.74	233.04
1.2	993.75	564.92	358.64	248.36
1.24	1045.77	596.76	374.09	263.36
1.28	1097.67	629.55	389.2	278.38
1.32	1149.84	663.69	404.44	293.68
1.36	1202.58	698.69	419.52	309.2
1.4	1256.81	735.37	434.7	324.96
1.44	1311.74	773.3	449.68	340.14
1.48	1367.3	812.27	464.99	355.37
1.52	1423.09	851.07	479.93	371.44
1.56	1479.42	889.94	494.34	387.67
1.6	1536.52	929.02	508.67	403.31
1.64	1594.85	968.84	523.08	418.94
1.68	1652.93	1008.59	537.32	434.94
1.72	1710.7	1048.84	552.01	451.05
1.76	1768.36	1089.31	566.67	466.46
1.8	1826.65	1131.05	581.42	481.32
1.84	1885.62	1173	594.48	496.33
1.88	1945.15	1214.87	598.66	511.51
1.92	2003.8	1256.69	608.16	526.56
1.96	2061.45	1299.15	626.28	541.97
2	2118.44	1341.76	643.96	556.78

Appendix H

Data

	Front force (grams)									
displacement	A	B	C	D	E	F	G	H	I	J
0.04	37.6	39.78	53.66	49.21	32.15	42.26	29.51	30.88	30.95	19.24
0.08	37.11	39.09	55.74	49.96	32.05	44.28	29.41	31.38	32.39	18.13
0.12	43.38	45.56	59.63	56.54	39.84	61.35	33.45	38.77	37.93	24.9
0.16	63.47	66.38	80.11	76.91	64.51	93.77	45.78	61.49	55.49	48.31
0.2	79.2	84.78	100.48	95.76	87.05	115.71	56.35	80.64	71.92	70.38
0.24	92.25	102.28	118.7	110.02	106.95	134.18	65.29	97.46	87.85	90.49
0.28	105.08	119.93	136.33	122.34	126.09	147.73	74.13	114.13	104.37	110.74
0.32	118.23	136.92	150.14	137.01	143.16	154.96	83.01	129.05	121.61	132.36
0.36	131.35	149.87	155.99	151.4	153.85	158.81	92.19	142.36	137.17	150.04
0.4	142.68	156.57	158.44	158.34	158.05	162.21	101.71	152	147.64	158.09
0.44	150.79	159.07	166.51	162.76	162.02	167.72	111.97	156.79	152.45	161.45
0.48	156.57	161.83	177.96	168.16	168.59	177.78	123.14	161.24	154.72	167.42
0.52	159.61	166.38	184.95	173.91	178.05	190.09	136.38	165.47	160	178.36
0.56	163.17	175.43	189.19	183.38	187.32	200.15	150.53	167.23	168.1	190.91
0.6	170.53	186	199.4	193.44	195.41	212.47	160.17	169.67	178.38	202.04
0.64	179.16	194.91	218.58	205.33	205.77	230.42	164.23	177.29	188.81	217.09
0.68	186.3	202.67	242.71	225.02	225.41	250.6	167.62	184.35	198.73	241.33
0.72	192.43	214.4	267.4	246.9	248.64	270.66	171.49	190.06	208.43	266.9
0.76	202.8	230.55	291.56	268.56	272.74	290.23	177.98	199.89	224.75	293.25
0.8	218.37	248.48	315.47	289.65	296.91	309.19	185.4	213.18	244.81	318.22
0.84	235.3	266.19	339.88	310.39	321.8	327.43	192.32	229.47	266.76	342.03
0.88	252.81	283.23	363.83	330.65	346.95	345.1	203.88	245.7	288.82	365.8
0.92	270.86	301.09	387.51	350.61	372.63	363.11	220	260.72	311.42	389.91
0.96	288.96	319.82	410.01	370.54	398.45	380.88	236.3	273.99	334.35	414.06
1	307.6	339.94	430.34	390.3	424.07	397.89	252.81	286.15	356.98	437.33
1.04	326.75	360.8	447.49	409.39	448.9	414.27	269.01	297.73	379.1	458.53
1.08	347.23	380.84	462.88	428.02	472.87	430.66	284.55	310.64	401.08	478.61
1.12	368.15	400.48	477.7	446.02	494.89	446.76	300.42	323.85	422.3	498.28
1.16	389.22	420.22	492.81	462.98	515.67	462.49	316.89	336.96	442.67	518.42
1.2	410.4	440.04	507.82	477.54	536.38	477.25	333.2	350.44	462.41	538.95
1.24	431.92	459.64	522.64	490.82	556.93	491.35	350.34	364.16	482.41	560.31
1.28	453.41	479.07	537.4	503.98	576.19	505.85	367.86	377.36	502.87	582.3
1.32	475.09	498.78	551.6	516.84	595.32	520.51	385.8	390.21	523.8	604.34
1.36	496.5	517.67	564.86	528.83	614.52	534.5	403.77	402.59	543.77	625.79
1.4	518.66	536.33	577.53	540.22	632.53	548.05	421.25	414.7	563.61	646.57
1.44	540.86	554.57	589.09	551.76	648.94	561.67	438.56	425.84	583.59	666.64
1.48	562.72	572.48	600.46	563.75	663.82	575.81	456.03	436.19	603.88	685.6
1.52	584.38	589.99	611.6	575.4	677.72	590.35	472.64	445.95	623.56	703.3
1.56	604.8	608.15	621.95	586.71	691.11	605.26	490.5	455.75	642.49	720.15
1.6	622.86	626.88	631.45	597.65	703.41	620.37	506.57	465.7	660.83	736.51
1.64	638.35	644.77	641.11	608.54	715.56	635.53	521.53	475.59	677.81	752.42
1.68	650.06	662.18	649.61	618.85	727.39	650.29	537.51	485.66	692.93	767.25
1.72	661.53	678.76	656.88	628.55	738.41	664.6	553.52	496.83	707.02	781.48
1.76	673.95	694.35	663.66	638.12	748.68	678	567.6	509.21	719.84	794.79
1.8	685.81	709.78	669.74	648.26	759.55	691.21	582.07	522.88	731.32	806.75
1.84	697.05	726.42	674.4	658.44	770.43	703.8	596.1	536.13	741.43	817.65
1.88	707.61	744.25	678.33	668.73	780.45	715.47	609.3	549.62	751.01	828.84
1.92	715.89	758.26	682.83	679.22	788.99	727.24	622.21	563.23	760.37	839.38
1.96	723.11	771.98	694.6	689.05	796.66	738.78	634.15	577.08	769.93	849.14
2	730.91	784.92	726.39	697.31	804.46	749.31	644.54	591.28	779.08	857.62

time Front	A	B	C	D	E	F	G	H	I	J
0.2	739.09	794.55	768.57	705.4	817.52	758.99	653.74	605.74	788.01	864.75
0.4	744.55	799.11	802.88	712.37	849.69	767.03	661.12	617.96	795.25	870.13
0.6	736.85	790.87	803.62	707.02	862.64	762.07	652.23	612.1	789.14	863.63
0.8	723.37	775	782.84	694.68	847.96	749.3	636.36	596.06	776.11	850.73
1	712.72	760.18	767.84	685.02	836.07	739.39	626.3	584.08	765.56	840.39
1.2	703.91	747.95	756.54	677.29	826.99	731.43	618.49	575.15	757.06	832.05
1.4	696.52	738.98	747.3	670.5	819.45	724.7	609.68	567.73	749.83	824.75
1.6	690.05	731.3	739.65	664.62	812.89	718.76	598.29	561.01	743.37	818.15
1.8	684.24	724.54	732.98	659.31	807.14	713.63	587.66	555.43	737.63	812.44
2	679.18	718.36	727.04	654.56	802.03	708.99	580.21	550.62	732.52	807.18
2.2	674.42	712.8	721.76	650.21	797.5	704.65	572.68	546.03	727.6	802.14
2.4	670.03	707.82	716.85	646.25	793.34	700.63	569.26	542.11	723.13	797.53
2.6	666.09	703.18	712.46	642.5	789.36	696.88	566.83	538.77	719.19	793.42
2.8	662.33	698.84	708.53	639.05	785.78	693.49	564.14	535.69	715.4	789.49
3	658.9	694.75	704.76	635.84	782.18	690.23	561.31	533.54	711.82	785.77
3.2	655.6	690.68	701.08	632.8	778.98	687.22	559.15	531.98	708.53	782.35
3.4	652.52	686.51	697.53	629.88	775.95	684.34	557.01	529.23	705.37	779.15
3.6	649.49	683.05	694.23	627.04	772.97	681.49	554.83	526.1	702.33	776.05
3.8	646.68	680.07	692.1	624.41	770.37	678.88	552.77	522.67	699.44	772.98
4	643.98	676.84	690.63	621.88	767.86	676.46	550.7	519.53	696.69	770.11
4.2	641.37	673.84	687.53	619.54	765.41	674.05	548.84	516.4	694.09	767.56
4.4	638.92	671.05	684.54	617.25	763.01	671.69	546.93	513.62	691.6	764.86
4.6	636.54	668.39	681.86	615.07	760.77	669.5	545.06	511.01	689.17	762.33
4.8	634.22	666.29	679.23	612.91	758.51	667.36	543.31	508.5	686.75	759.93
5	630.23	661	674.2	609.04	754.23	663.25	540.03	504.61	682.48	755.34
5.2	628.29	658.6	671.89	607.18	752.37	661.36	538.46	502.88	680.5	753.22
5.4	626.26	656.23	669.73	605.29	750.73	659.58	537.02	501.21	678.48	751.16
5.6	624.47	653.92	667.53	603.63	749.03	657.78	535.51	499.82	676.6	749.14
5.8	622.62	651.8	665.28	602.07	747.32	656.11	534.08	498.69	674.58	747.09
6	620.77	649.76	663.29	600.52	745.7	654.41	532.62	497.66	672.76	745.12

	Side force (grams)									
displacement	A	B	C	D	E	F	G	H	I	J
0.04	44.47	28.82	34.64	45.44	32.62	19.53	32.87	15.64	26.29	45.89
0.08	44.14	28.41	37.22	45.05	32.45	18.88	32.85	15.76	26.04	46.68
0.12	51.98	34.42	46.83	53.98	41.22	20.6	38.92	19.47	32.26	51.39
0.16	77.19	53.3	74.4	82.84	68.8	33.48	58.4	31.05	51.74	79.64
0.2	99.02	70.12	98.03	109.08	93.4	45.08	76.66	40.96	68.03	108.26
0.24	118.85	85.33	119.91	132.13	115.85	55.77	94.4	50.12	81.96	130.2
0.28	137.83	100.26	139.22	146.97	134.47	69.25	112.79	59.86	95.85	142.4
0.32	148.77	114.81	151.09	152.87	144.01	84.8	131.05	69.93	109.83	147.64
0.36	151.7	129.35	156.72	156.19	148.12	101.04	147.17	80.07	123.82	149.87
0.4	154.97	141.81	160.41	166.97	152.04	118.91	156.12	90.28	136.85	160.69
0.44	166.49	150.96	166.47	180.99	160.88	136.98	159.06	100.87	148.95	176.41
0.48	180.75	156.61	180.37	190.29	172.64	148.69	162.8	111.72	157.72	191.53
0.52	193.3	159.25	194.47	197.72	185.28	152.53	168.95	122.36	162.11	202.66
0.56	201.57	163	209.25	214.8	201.27	158.65	177.85	132.28	164.31	209.87
0.6	217.82	171.34	227.99	241.76	216.27	170.82	191.22	142.61	166.65	226.14
0.64	243.02	182.84	254.11	269.66	230.95	183.63	202.99	151.81	170.59	252.9
0.68	270.31	195	282.02	297.65	251.28	192.1	219.34	156.98	176.37	280.5
0.72	296.98	204.78	309.13	325.16	274.88	197.79	244.71	160.19	183.65	308.08
0.76	322.87	217.88	335.89	352.18	299.05	209.38	271.58	161.75	190.89	335.86
0.8	349.14	236.03	362.33	378.98	322.46	227.68	297.72	164.65	200.18	363.61
0.84	375.1	258.16	387.67	405.47	345.42	247.47	322.25	171.38	217.78	391.16
0.88	401.28	280.42	410.71	430.53	367.07	266.67	346.4	181.38	237.47	418.4
0.92	429.97	302.92	433.69	453.15	391.41	285.39	372.37	189.46	255.88	443.92
0.96	458.38	325.38	457.1	471.83	418.95	303.72	396.82	197.01	273.8	467.4
1	486.32	347.73	480.4	488.53	444.34	321.95	420.55	211	292.64	491.61
1.04	513.83	370.07	502.64	505.38	468.22	338.84	443.88	230.02	310.89	516.06
1.08	540.38	392.21	524.09	523.58	492.94	354.84	466.46	250.96	329.84	539.34
1.12	565.92	413.21	545.53	542.25	509.59	371.63	488.13	271.35	349.76	560.92
1.16	591.87	433.16	567.28	560.32	524.4	389.97	508	291.46	369.69	582.1
1.2	616.6	451.86	587.8	577.06	541.53	407.73	526.69	313.08	388.94	603.23
1.24	639.71	469.52	607.32	592.77	559.46	424.66	545.65	335.97	408.07	624.46
1.28	661.68	484.98	626.71	608	584.36	441	565.24	357.27	426.57	645.16
1.32	682.89	499.47	645.99	623.4	595.72	457.16	585.26	378.13	444.37	665.07
1.36	703.09	514.14	663.77	637.56	610.37	472.41	603.95	398.88	461.66	684.19
1.4	722.52	529.52	679.64	650.68	626.66	487.57	621.47	419.6	479.19	702.86
1.44	739.05	544.98	694.01	663.32	641.07	502.57	638.31	440.13	496.96	720.46
1.48	755.28	560.39	707.14	675.74	665	517.63	654.31	460.01	514.48	737.24
1.52	771.26	576.14	718.73	686.87	688.17	533.3	669.69	478.93	531.38	753.25
1.56	783.4	592.09	728.99	697	708.68	549.32	684.76	497.71	548.57	768.17
1.6	794.85	607.26	739.22	705.69	727.31	565.14	699.39	516.37	566.12	782.09
1.64	808.24	622.05	749.27	714.27	745.12	580.96	714.53	534.94	583.85	795.37
1.68	820.06	636.05	757.01	721.96	761.19	596.7	728.46	553.41	601.03	807.94
1.72	831.86	649.89	763.53	727.21	776.16	612.67	742.41	571.56	617.56	820.23
1.76	843.43	662.99	769.61	730.22	790.01	628.17	757.01	589.55	633.76	831.49
1.8	854.79	675.93	776.86	732.67	803.11	643.21	771.21	607.62	649.21	842.39
1.84	864.08	689.89	803.86	738.28	814.29	657.7	784.47	625.13	663.63	852.61
1.88	870.46	703.24	853.21	767.69	824.89	671.34	796.99	642.13	677.12	861.38
1.92	874.61	714.82	902.83	815.09	835.18	684.29	807.35	658.09	689.74	868.55
1.96	876.76	726	947.31	857.69	841.09	696.57	815.15	673.25	701.91	874.35
2	875.6	735.55	988.7	896.19	846.56	709.06	820.51	687.67	713.56	879.39

Appendix I