DEVELOPMENT AND APPLICATION OF THE SECOND-GENERATION BERRY IMPACT RECORDING DEVICE

by

RUI XU

(Under the Direction of Changying Li)

ABSTRACT

Instrumented sphere is a useful tool to evaluate impact damage to fruits during harvesting and post-harvest handling. In previous studies, a miniature instrumented sphere, known as Berry Impact Recording Device (BIRD I), was developed to measure the impact damage for small fruits and vegetables. In this thesis, an improved BIRD sensor (BIRD II) with smaller size, lighter weight and better performance was developed. The sensor can better resemble the behavior of a real blueberry under dynamic impacts. Both the BIRD I and BIRD II sensors were used to evaluate eleven commercial blueberry packing lines. There were many transfer points that created high impact level and most of them had hard surfaces. These impacts could cause the fruit bruising rate up to 26% for a particular cultivar. The results also showed that padding the transfer points is an efficient and inexpensive way to reduce impacts.

INDEX WORDS: Sensors, Instrumented sphere, Blueberry, Packing line, Impact damage, Miniature, Bruising, Food Quality

DEVELOPMENT AND APPLICATION OF THE SECOND-GENERATION BERRY IMPACT RECORDING DEVICE

by

RUI XU

BE, China Agricultural University, China, 2011

A Thesis Submitted to the Graduate Faculty
of The University of Georgia in Partial Fulfillment
of the
Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2014

DEVELOPMENT AND APPLICATION OF THE SECOND-GENERATION
BERRY IMPACT RECORDING DEVICE

by

RUI XU

Approved:

Major Professors: Changying Li

Committee: Zion Tse
Anish Malladi

Electronic Version Approved:

Julie Coffield
Interim Dean of the Graduate School
The University of Georgia
December 2014

DEDICATION

TO

MY PARENTS

XUEJUN XU AND WENLIN QI

FOR GIVING ME UNCONDITIONAL SUPPORT ALL THE TIME

ACKNOWLEDGMENTS

I would like to express my thankfulness to my major professor, Dr. Changying Li who mentored me in the past two and half years. I appreciate his encouragement and guidance to me which helped me to grow towards a mature researcher. Without his effort on the project, this thesis would not be fruitful.

I also would like to thank Dr. Zion Tse and Dr. Anish Malladi who provide resources and suggestions for my project. I am very grateful to the project collaborators Dr. Fumi Takeda and Dr. Gerard Krewer who led the field tests in the past two years. Without their help, the field tests would not be accomplished.

I would like to express my appreciation to all my lab colleagues. Especially I would like to thank Dr. Weilin Wang, Dr. Adnan Mustafic and Mr. Tharun Kumar Konduru who are always willing to share their research experience with me and gave me constructive suggestions. Special thanks to Yu and Yuri who helped me do experiments in the field. Thank all my friends in Athens for their kind help and moral support.

Finally, I would like to acknowledge the funding support of USDA National Institute for Food and Agriculture (NIFA) Specialty Crops Research Initiative (SCRI) and US Highbush Blueberry Council (USHBC).

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

Blueberries rank as the second most important commercial berry crop in the United States. Over the past thirty years, the United of States has been the world's largest blueberry producer and the production has gained 6 folds increase. In 2013, there were 515 million pounds of cultivated and 80 million pounds of wild blueberries harvested and utilized in the United States, creating 801 million dollars value for blueberry farmers [1]. The harvested blueberry are either marketed fresh or processed to make blueberry products. However, because of the high market value of fresh blueberries (1.197 dollar per pound compared to 0.673 dollar per pound for processed blueberries in 2013), over 55% of the cultivated blueberries were sold in fresh market [2].

Blueberry is susceptible and sensitive to mechanical damage. As a type of stress that occurs during harvest and post-harvest handling of fruit, the mechanical damage changes physiological and morphological properties of fruit, resulting in bruising or defect, and thus affects the fruit quality and shelf life [3]. There are two different types of mechanical damage during harvest and post-harvest handling: dynamic impact that occurs when fruits collide with mechanical parts and static load caused by compression during packing, storage, or transportation [4]. Before reaching consumers, blueberries need to be handled at different stages, such as harvesting, packing, storage, and transportation from the field to the packing house or grocery stores. Blueberries can experience both types of mechanical damage at each of these stages. However, the dynamic impact which mainly originates from machine harvesters and packing lines is typically the main reason that causes the blueberry bruising since the blueberries are packed into clamshells to avoid large load on the fruit.

Traditionally, blueberries are hand harvested by human labor, which is inefficient and expensive, requiring as many as 600 h of labor per acres [5]. The labor cost for hand harvesting can be as high as $0.5- 0.7/lb for southern highbush blueberries [6]. As a result, the usage of machine harvester is increasing recently due to its high efficiency and low cost. For example, an over-the-row mechanical harvester can improve the worker productivity by 60 times and reduce the cost by 85% [7]. However, the greatest challenge for mechanical harvesting is the high rate of bruising caused by the dynamic impacts during harvesting when berries drop on a hard surface from a height as high as 2 m. About 78% of the mechanically harvested blueberries are bruised compared to 23% for hand packing [7]. The bruising of the blueberries makes them unmarketable on fresh market, causing a substantial economic loss consequently. It was reported that only 23% of the machine-harvested cultivated blueberries are used fresh compared to 82% for hand-harvested fruits [8].

In addition to the impact damage caused by machine harvesters, the blueberries (either hand-picked or mechanical harvested) can be damaged by packing lines. Similar to machine harvesters, dynamic impacts happen when berries collide with the hard surface and experience multiple drops during packing. Brown et al. reported that blueberry started to bruise at 150 mm drop height on hard surface and the bruise rate increased linearly to 50% at 300 mm and 100% at 600 mm, while hard surface drop of 150 to 300 mm have been observed on many packing lines [7]. Therefore, it is likely that the blueberry packing line can cause fruit bruising although no study was done to evaluate blueberry packing lines. Previous research has been focusing on evaluating packing lines for other types of fruits and vegetables, for example, apple, tomato and potato [9, 10, 11]. It was reported that the apple packing line can cause 194 to 581 mm^2 accumulated bruising area for each fruit which is large enough to degrade the fruit and result in a loss of income [12].

In order to understand the impact damage caused by packing lines, the instrumented sphere (IS) was developed and used to quantitatively measure the impact and identify when and where the impact occurs. Research has shown that the IS is capable of recording the impact amplitude and identifying the location of the impact in combination with a video camera. Previous ISs are mainly designed for large fruits and vegetables and are not suitable to apply on small fruits. For example, the smallest commercial IS, Impact Recording Device (IRD), has a size of 57 mm to 89 mm which is much larger than a typical blueberry (15-20 mm)[13]. Therefore, developing an IS for small fruits like blueberries will greatly aid researchers in understanding the mechanical interaction between small fruits and machines, and improving the design of harvesting machines, packaging lines, etc.

To quantitatively measure the mechanical impact generated by blueberry machine harvesters and packing lines, the first generation of Berry Impacting Recording Device (BIRD I) was developed. The BIRD I sensor has a size of 24.5 mm in diameter and weight of 14 grams, which is slightly larger and much heavier than a typical blueberry (the size is between 7 mm to 23 mm and the weight is between 0.25 g to 3.91 g). The sensor has been successfully used in evaluating different types of blueberry machine harvesters [14, 15]. However, it has not been utilized to evaluate the blueberry packing lines. Therefore, the primary goal of this research reported in the thesis was to develop the second generation BIRD (BIRD II) sensor with smaller size, lighter weight, and better overall performance. In addition, various commercial blueberry packing lines were tested using both BIRD I and BIRD II sensors.

1.2 Objectives

The work described in this thesis has two primary objectives: 1) to develop the second generation BIRD sensor and 2) to evaluate commercial blueberry packing lines. The detailed objectives of this research were to

- Develop the hardware and software of the BIRD II sensor;
- Calibrate and characterize the BIRD II sensor;
- Evaluate commercial blueberry packing lines using BIRD I and BIRD II sensors.

1.3 Thesis Overview

The first chapter of this thesis describes the background, rational, motivation and objectives of the study. It also outlines the structure of the thesis. Chapter 2 demonstrates the hardware and software design of the BIRD II sensor. The hardware design includes the circuit board and sensor housing. The software includes the microcontroller program that makes the sensor functional and the PC program used to interface the sensor and process the data. Chapter 3 describes the calibration and characterization of the BIRD II sensor. Comparison of the performance between the BIRD II and BIRD I sensor is also presented. Finally, Chapter 4 discusses the results and concludes the research. Potential improvement of the current work and other promising applications of BIRD II sensor are also discussed in Chapter 4.

CHAPTER 2

DEVELOPMENT OF THE SECOND GENERATION OF THE BERRY IMPACT RECORDING DEVICE[1]

[1]R. Xu, C. Li. To be submitted to *Sensors*.

2.1 Introduction

Blueberry, along with other berry fruits, are perishable and can be easily bruised during harvesting and post-harvest handling due to a large number of mechanical impacts created by machine parts. It was estimated that about 78% of mechanically harvested blueberries are bruised and unmarketable [7]. Therefore, it is important to fully understand how the blueberry interacts with the machine parts during machine harvesting and handling in order to reduce bruising.

The idea to design a sensing tool to quantitatively measure the mechanical damage during harvesting and post-harvest handling has been put forward by the researchers since early 1970s with the concept of instrumented sphere. Essentially, an instrumented sphere (IS), also known as the pseudo fruit, is a standalone data logging device that can measure and record the mechanical impacts experienced by agriculture products. Herold et al defined three technical requirements for an instrumented sphere: 1) the physical property (e.g. size, mass, shape and elasticity) of the sphere should be similar to the property of the real object it tends to measure; 2) it should be able to detect the mechanical damage including dynamic impacts and static load; and 3) the way that it goes through the practical harvesting and handling processes should represent the way that the real produce does [16]. The second requirement highlights the essential functions of an IS and inspires two different technical directions that have been used by researchers: one uses accelerometers to measure dynamic impacts and the other uses pressure sensors to measure static load. Some early models of accelerometer-based IS were capable of recording all impact events above a programmed threshold based on measuring the acceleration but were not able to detect static load [17, 18, 19]. Therefore, the second research direction of IS was brought up by Herold et al. who designed a pressure measuring sphere (PMS) and its advanced version PMS 60 [16]. The PMS 60 can record static load as well as dynamic impact, but the error (22% variance at sphere single orientation) is five times higher than the static load. Some commercialized ISs were introduced into the market, including Impact Recording Device (IRD, Techmark Inc., Lansing, Michigan USA), the Smart Spud (Sensor Wireless, Canada) and PTR 200 (SM Engineering, Denmark).

However, these commercially available ISs were mainly designed for large fruits and vegetables and none of them can be readily applied to small fruits like blueberry due to a significant difference in size and weight. For example, the size and shape of IRD, PMS60, and PTR200 are 57 mm sphere, 62 mm sphere, and 53×53×83 mm semi-ellipse, respectively. Their weights are 89 g, 180 g, and 170 g, respectively. In contrast, the size of the blueberry is between 7 mm to 23 mm and the weight is between 0.25g to 3.91g [20]. Therefore, developing an IS for blueberry must overcome the challenges of reducing the size and weight of the IS to the range that is comparable to a typical berry fruit. Other challenges include low power consumption with small size battery, large impact detection range and proper casting material of similar surface properties with blueberry.

In a previous project, Yu et al. designed the first generation of Berry Impact Recording Device (BIRD) sensing system, consisting of a BIRD I sensor, an interface box and PC software [21, 22]. The size of the BIRD sensor is 1 inch (25.4 mm) in diameter, similar to a large size blueberry (23 mm). Its weight (14 grams), however, is much greater than that of a normal blueberry. The primary objectives of this study were to develop and characterize the second generation BIRD (BIRD II) sensor with smaller size, less weight, lower power consumption and lower cost than BIRD I, enabling it to better simulate real berry fruits. Other enhancement of the sensor includes removing interface box by implementing the Universal Serial Bus (USB) in the sensor and improving the sensor and PC software design. The performance of the BIRD II sensor was also characterized and compared with BIRD I.

2.2 Hardware Design

The size of BIRD I is constrained by the size of the circuit board (19.4 mm in diameter) and the coin battery (20 mm in diameter). Therefore, electronic components in smaller dimensions were chosen to reduce the size of the circuit board for BIRD II. In order to reduce the size of BIRD II and maintain a similar performance with BIRD I, a tri-axial accelerometer was chosen to replace the three single-axis accelerometers used in BIRD I. A battery with smaller size was also selected to replace the coin battery in BIRD I. The final size of the BIRD II (Figure 2.1) is 21 mm in diameter and the weight is 6.9 grams, which is reduced by 17% in size and 50% in weight compared to BIRD I. Most parameters of BIRD II are maintained the same as or better than BIRD I (Table 2.1). The sensing range and maximum sampling frequency of BIRD II are reduced compared to BIRD I but are still technically adequate to record and assemble most impacts occurred in the field. Unlike BIRD I and other ISs, BIRD II can be directly connected to PC through a Universal Serial Bus (USB) cable without an interface box, which significantly simplifies the operation of the sensor and reduces the possibility of malfunction of the sensor in the field. Due to these improvements, the total cost of BIRD II is also reduced significantly (by 78%) compared to BIRD I.

As a recording device, the basic functions of BIRD II are to measure the acceleration, store the data into memory and transfer the data to the computer. Therefore, the sensor should have an accelerometer to measure the acceleration, an onboard memory to store the data, a microcontroller to control other units and a battery to power the sensor. To maintain a reasonable data collection performance, the sensor should have enough sampling frequency to avoid aliasing and sufficient measurement range and accuracy to record critical impacts. Due to the capacity of the battery, the selected electronic components should have low power consumption in order to maximize the operation time. Additionally, the selected microcontroller should support USB protocol in order to connect BIRD II with the PC directly without an interface box. Overall, BIRD II (Figure 2.2) consists of four essential parts: a tri-axis accelerometer (ADXL377), a 1Mb Ferroelectric Random Access Memory (F-RAM) chip (FM25V10), a microcontroller (PIC18LF14K50), and a rechargeable battery (PGEB201212). Other low power components were also chosen. The performance of the main components was discussed blow.

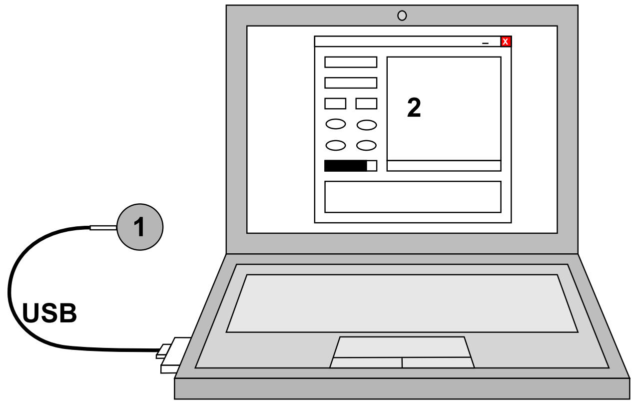


Figure 2.1. Connection between BIRD II and PC through a USB cable with a customized connecter in the sensor end. The diagram was not drawn in scale. 1: BIRD II. 2: PC and BIRD II PC software.

2.2.1 Accelerometer

The first generation BIRD sensor (BIRD I) uses three 500 g single-axial accelerometers to record the impacts, which provide a large sensing range up to 866 g for the sensor. However, using three accelerometers also constrains the further reduction of the size of the BIRD sensor and the large sensing range also reduces the sensitivity of the accelerometer. In order to reduce the size of the sensor, a trial-axial analog Microelectromechanical systems (MEMS) based accelerometer (ADXL377, Analog Device, Norwood, Massachusetts, USA) is used in BIRD II. It has $\pm$200 g sensing range in each axis with a typical sensitivity of 6.5 mV/g, three times of that of BIRD I. Additionally, ADXL377 has low power consumption with a typical 300 μA current drain and a small size package (3$\times$3$\times$1.45 mm), which are both essential criteria for the selection of the accelerometer. The maximum bandwidth of ADXL377 is 1 KHz in each axis which requires at least 2 KHz sampling rate.

From the previous tests for blueberry machine harvesters using BIRD I, the results showed that the duration of the impacts on average was 5-10 ms and the magnitude of most impacts were under

Table 2.1. Comparison between BIRD I and BIRD II.

Parameter	BIRD I	BIRD II
Size	Φ25.4 mm	Φ21 mm
Weigh	14 grams	6.9 grams
Sensing range[1]	-500g - 500g for each axis	-200g - 200g for each axis
Sensitivity	2.2 mV/g	6.5 mV/g
Sampling frequency	Up to 3 KHz	Up to 2 KHz
Memory	Up to 9000 datasets	Up to 16384 datasets
Operation Time	4 hours	4 hours
Connectivity	Serial communication through an interface box	USB 2.0 with customized connector
Material Cost[2]	$356.89	$79.68

400g [14]. Preliminary packing line tests using BIRD I also showed that most impacts are less than 200g. Therefore, the sensing range and bandwidth of ADXL377 are sufficient to record most impacts without aliasing.

2.2.2 Memory

The choice of the data storage is evaluated from three main criteria: the writing speed of the memory should be fast enough to store the data at a high frequency (up to 2 KHz), the power consumption should be small, and the capacity of the memory should be large enough to store sufficient data points. Other criteria such as long life cycle and small package are also considered. According to these criteria, a serial F-RAM chip (FM25V10, Ramtron, Colorado Springs, Colorado, USA) with 1Mb capacity was used in BIRD II. FM25V10 has a fast Serial Peripheral Interface (SPI) with a 40MHz maximum clock speed which provides sufficient data transfer speed. With an optimized data storage structure, the memory can save up to 16384 impacts data points.

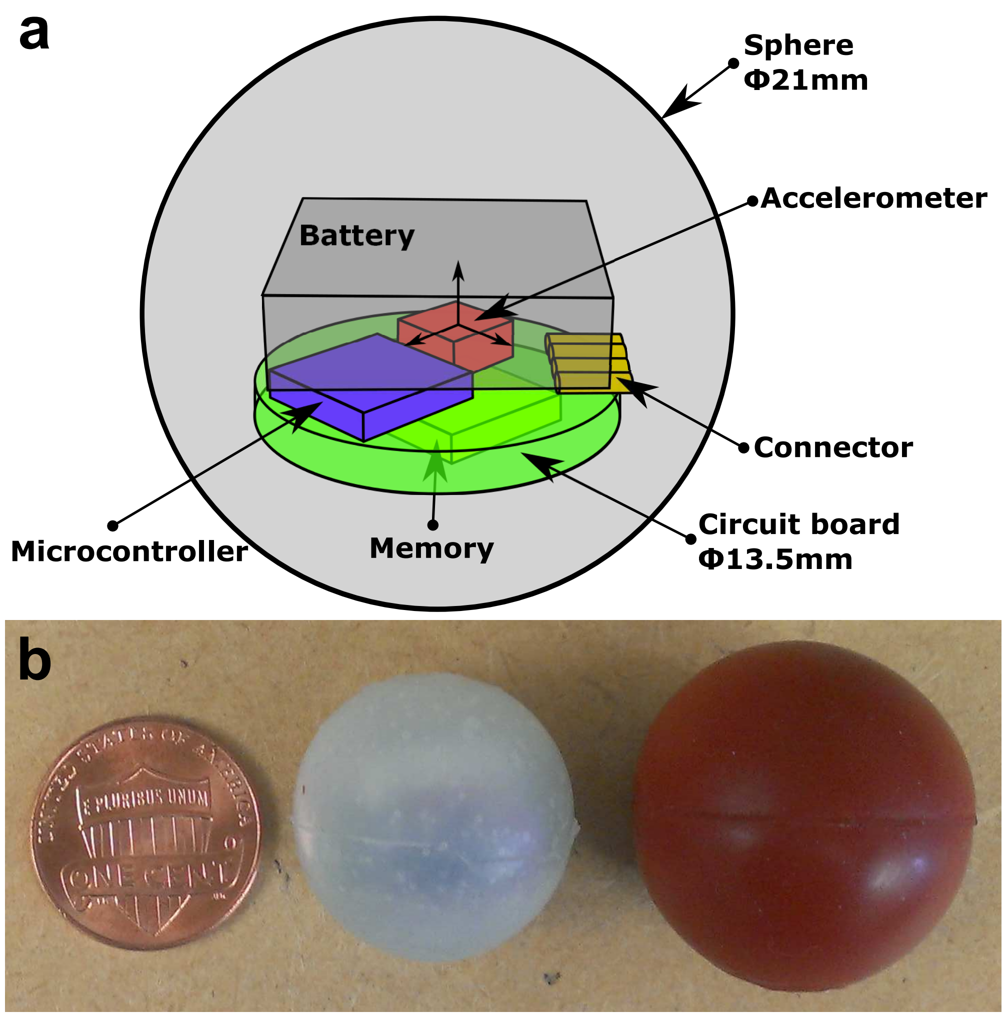


Figure 2.2. Structure of BIRD II (a) and size comparison of a penny, BIRD II and BIRD I (from left to right) (b).

Microcontroller

The selection of microcontroller is targeted on fast operation speed, low power consumption and small package size. Because the microcontroller needs to transfer data to memory chip and converts the analogy signal from the accelerometer into digital counts, the microcontroller needs to integrate SPI and Analog-to-digital converter (ADC) modules. Therefore, an 8-bit micro-

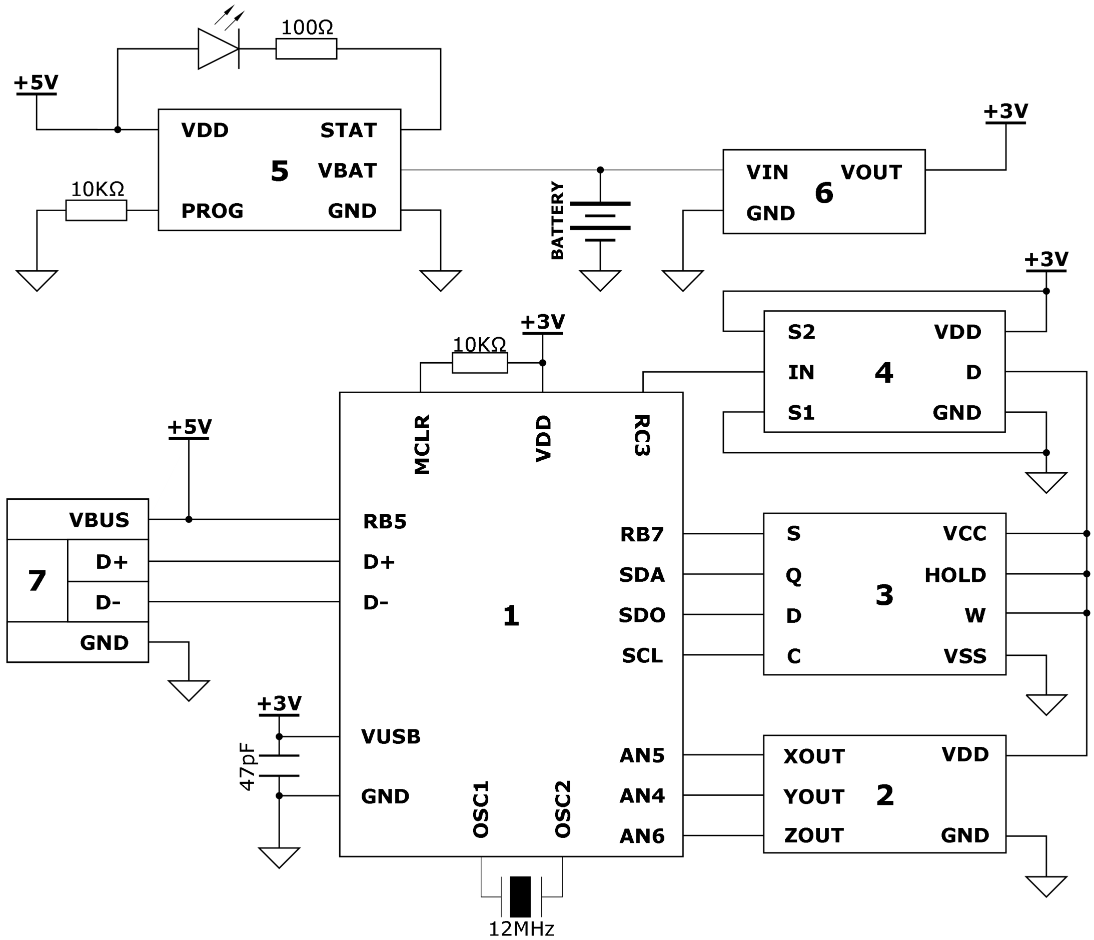


Figure 2.3. Schematic diagram of the circuit board. 1: Microcontroller. 2: Accelerometer. 3: Memory. 4: Analog switch. 5: Recharger. 6: Voltage regulator. 7: USB Connector.

controller (PIC18LF14K50, Microchip, Chandler, Arizona, USA) was selected for this reason. PIC18LF14K50 has a 10-bit ADC with 9 external channels, a Master Synchronous Serial Port (MSSP) module which can be used as SPI, and a Universal Serial Bus (USB) module which is compliant with USB V2.0 standard. It has a 16-bit timer which can be used to generate accurate system clock for BIRD II. The microcontroller is implemented with nanoWatt XLP technology, consuming a small current drain in the active (8 mA) and sleep mode (24 nA). Its program memory and data memory are 16 K and 768 bytes, respectively, which are sufficient for programming and data manipulating.

2.2.3 Universal Serial Bus

The Universal Serial Bus (USB) is an industrial standard that is widely used for connection, communication and power supply between computer and other electronic devices. Using the build-in USB transceiver in the microcontroller, BIRD II implemented USB 2.0 protocol and only four wires are needed to set up communication with computers. As a result, the interface box is no longer needed for BIRD II , which greatly simplifes the connection between the sensor and computer compared to BIRD I. The communication speed for USB (12 Mbits/s) is also substantially faster than serial communication (115.2 Kbits/s). Consequently, the data downloading time is significantly decreased from 103 seconds for BIRD I to 8 seconds for BIRD II. In addition to acting as a communication bridge between the sensor and the computer, the USB also can charge the sensor through the VBUS line (Figure 2.3).

2.2.4 Power Supply

Since the size of the battery is constrained by the miniature size of the sensor, a high density battery is desired to maximize the operation time of the sensor. Among commercially available batteries with high density and small package, a Lithium-ion rechargeable battery (GM041215-PC, Lund Instrument Engineering, Inc., Orem, Utah, USA) with 3.7 V output voltage and 45 mAh capacity was selected. The dimension of the battery is $12\times10\times4$ mm and its weigh is 1 gram. The battery also comes with a battery protection circuit board that can prevent it from over discharging and charging. A linear charge management controller (MCP73831, Microchip, Chandler, Arizona, USA) was applied to charge the battery through USB. As shown in the circuit schematic (Figure 2.3), the VDD of the charging controller is directly connected to the power line of the USB port so the battery can be charged as long as the sensor is connected with the PC. In order to extend the working time of the sensor, low power chips were used and the hardware and software were carefully designed to reduce the overall current drain to a desired range. A linear low-dropout (LDO) regulator (MCP1700, Microchip, Chandler, Arizona, USA) was employed to regulate the battery voltage to 3.0 V to provide steady power supply for other parts of the circuitry. The microcontroller is directly powered by 3.0V while the accelerometer and memory are connected to 3.0V through an analog switch (ADG752, Analog Device, Norwood, Massachusetts, USA) so that the microcontroller can turn them on or off according to different power consumption requirements.

The charging and discharging performance of BIRD II was tested using the following procedure. After fully recharging the sensor and making it sample at maximum sampling frequency, the voltage of the battery was recorded until the battery was fully discharged. Then the sensor was charged by the computer via USB cable and the voltage of the battery and the recharging current was recorded until it was fully charged (recharging current became zero). The discharging curve (Figure 2.4.a) shows the battery reached the cutoff voltage (3.6V) at 4.2 hours with an 8.21mA discharging current, indicating the sensor can work at least four hours. The charging curve (Figure 2.4.b) shows the battery can be fully charged in less than an hour.

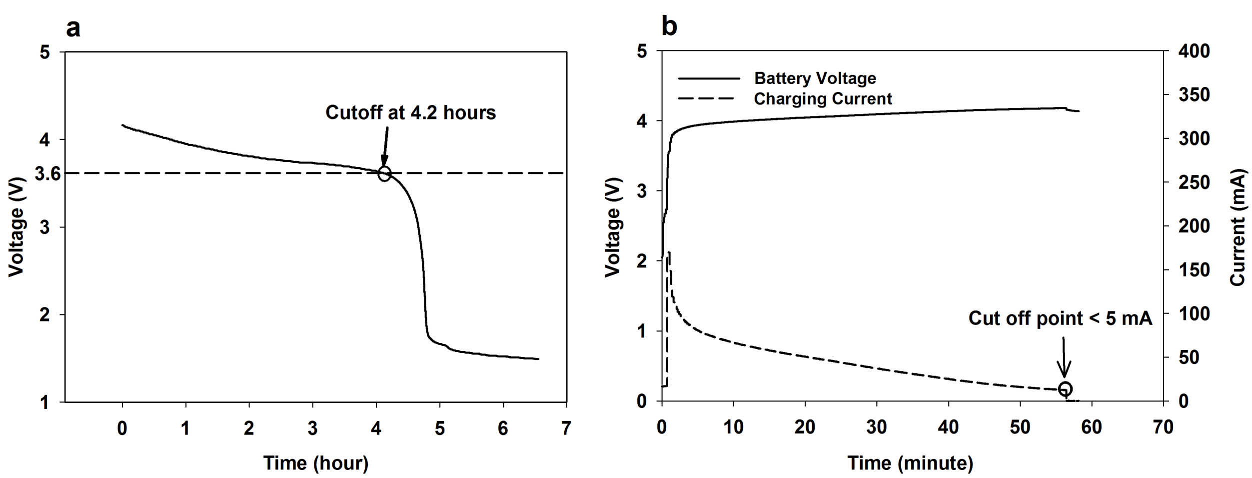


Figure 2.4. Battery discharging curve (a) and charging curve (b).

2.2.5 Housing Design

The circuit board and battery was directly cast into a 21 mm (in diameter) sphere using silicon rubber (AM 128T, AeroMarine Products Inc., San Diego, California, USA) (Figure 2.a). According to the manufacture's data sheet, the tensile strength at 400% elongation of the silicon rubber is 3.96 MPa, which is equivalent to a Young's modulus of 0.79 MPa. The final size of BIRD II was reduced by 17% compare to BIRD I. The weight of the sensor is 6.9 grams, which is reduced by 50% compared to BIRD I. The weight distribution of the BIRD I and BIRD II is listed in Table 2.2, which shows the weight reduction is mainly contributed by the reduction of battery and the housing material.

Table 2.2. Weight distribution of BIRD I and BIRD II (gram).

Sensor	BIRD I	BIRD II
Circuit board	1.9	1.2
Battery	3.3	1.2
Housing	8.8	4.5
Total	14	6.9

2.3 Software Design

2.3.1 Sensor Program

The sensor can operate at three different modes (Figure 2.5) - sleep, communication and sampling mode - based on different power consumption level and functions of the sensor. Once the sensor is powered on, it makes necessary initialization for the hardware and program, then it goes to sleep mode by default. Under sleep mode the accelerometer and memory are powered off and the microcontroller is suspended and only respond to external interrupt. Therefore, the power consumption of the sensor will maintain at the lowest level with a current drain of 0.01 mA. The sensor will change to communication mode after being connected to the PC to receive and process commands from the PC. A simple communication protocol (Figure 2.3) was used to transmit commands and data between the sensor and PC. After receiving a command, the sensor executes the command according to the command type (indicated by different letters). For example, if the sensor received "start to sample" command, the sensor will set the frequency, threshold and system time based on user's setting in the PC program, then erase the sensor memory and set the sensor to sampling mode. The sensor starts to sample only after being disconnected from the PC.

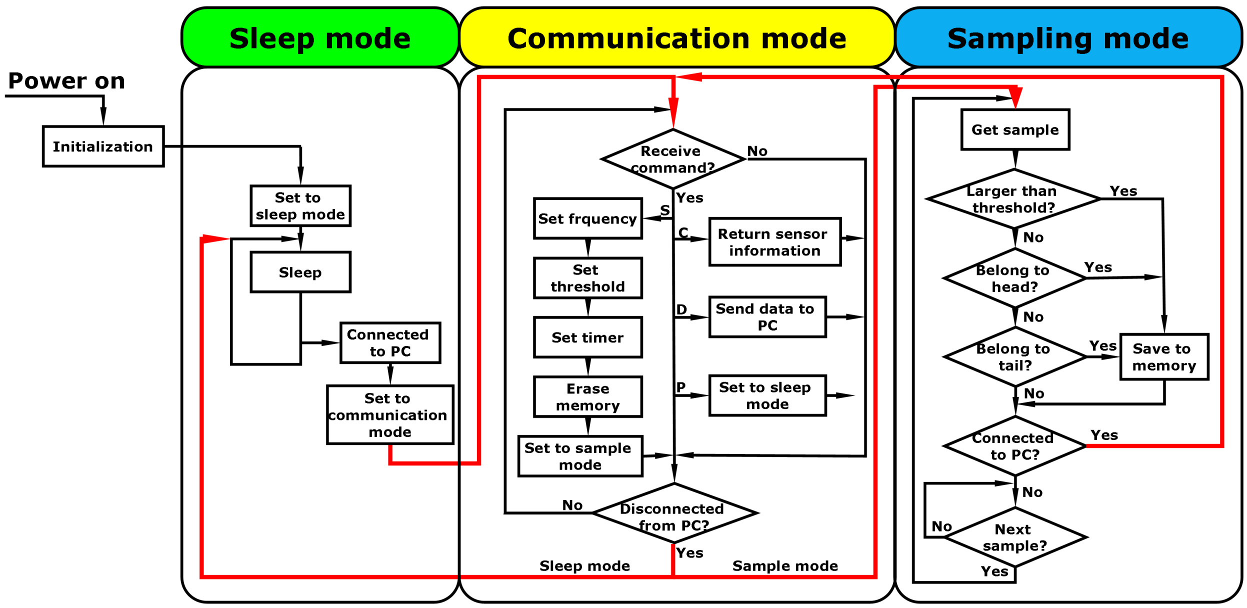


Figure 2.5. Flowchart of the sensor program. 'S': configure sensor and set sensor to sampling mode. 'C': request sensor information. 'D': upload sensor data to PC. 'P': Set sensor to sleep mode. These letters indicate different type of command.

Table 2.3. Structure of the communication protocol.

Bytes	Field	Description
1	Head	Start of the command.
1	Status	Whether the commend is executed correctly or not.
1	Command	Command type.
2	Data length	Length of the data transmitted in the command.
N	Data	Data transmitted in the command. The length of this field is indicated by the data length field.
1	End	End of the command.

In the sampling mode, the sensor measures the acceleration and stores the results into the memory at a sufficient frequency. A typical impact is in bell curve shape. A user-defined threshold is used to avoid recording trivial impacts that are below the threshold. To make the impact curve complete, certain data points below the threshold are also recorded: seven before and seven after the impact curve, defined as leaders and trailers, respectively. In each sampling cycle, the sensor first converts the analog acceleration voltage into digital value, and then compares with the threshold using the summation acceleration which is defined as the scalar value of the vector summation of the three axes [21]. If the summation acceleration is greater than the threshold, the acceleration value, as well as the leaders and trailers of that impact will be written to the memory.

The sensor describes the system time using UNIX time, defined as the number of seconds that have elapsed since 00:00:00 Coordinated Universal Time (UTC), Thursday, January 1st, 1970. The sensor uses ticks to describe time within one second, where one tick is equal to 0.5 ms. Therefore, the maximum sampling frequency of the sensor is 2 KHz. At the start of the sampling, the starting time is stored to the memory as a 64-bit long dataset (Figure 2.6.a). The PREFIX is fixed as 0x3FFF, which is used to differentiate the starting time from impact datasets. The time information is stored as UNIX time and ticks.

Each data point consists of the acceleration of three axes and the relative time to the start of the sampling mode. The sensor stores the data points into memory as datasets. Each dataset is 64-bit long and composes of three sections: 2 bits of data type, 30 bits of digital count of the acceleration of three axes, and 32 bits of relative time (Figure 2.6.b). The data type is used to differentiate data points between successive impacts by alternating it between 0x01 and 0x02 and the change of the data type indicates the data points belong to a new impact even. The relative time is described as multiples of ticks. The absolute time of the data point are expressed as the addition of the relative time and the starting time of the sampling. With the structure of the dataset, one data point in the impacts only occupies 8 bytes in the memory compared to 13 bytes in BIRD I. Therefore, the memory can store up to 16384 data points, which is 82% larger than what BIRD I can store (9000 data points) [22].

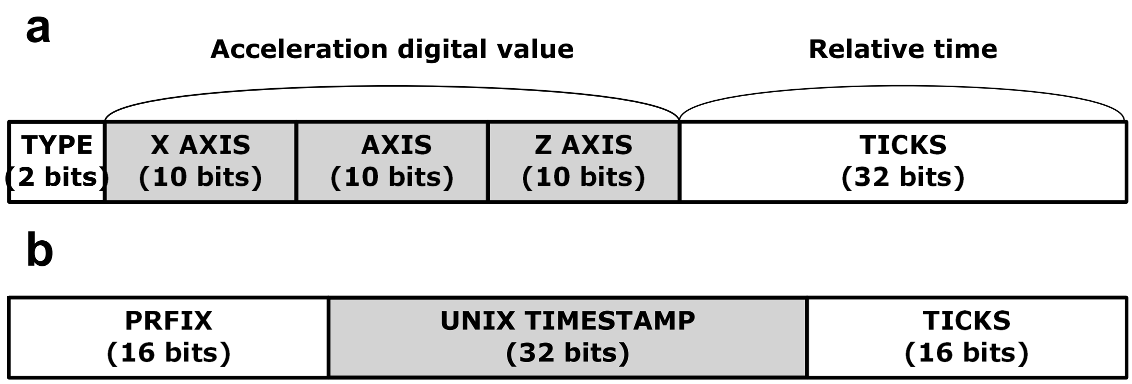


Figure 2.6. Structure of the dataset for the starting time (a) and data points (b). One tick is 0.5 ms.

2.3.2 "pBIRD" PC Program

In order to manage the sensor, a PC program was designed using LabVIEW 2013 (National Instruments, Austin, TX, USA) due to its strengths in communicating with hardware and its ease of programming for data presentation and processing. The PC program has three main functions: sensor configuration, data processing, and video analysis. These functions are accomplished by a main program (Figure 2.7) and a sub program (Figure 2.8). The main program was used to configure the sensor and process the raw data. The subprogram was designed to link the video taken in the field with the sensor data based on the time information so that the location of the impacts can be identified from the video. The video analysis function greatly simplified the process to analyze the video compared to manual checking.

Initially, the PC program disables the sensor configuration function until the program successfully connects with the sensor and retrieves the sensor information which includes the sensor ID, size and weight of the sensor, and calibration coefficient. The sensor is configured using the following sequence (Figure 2.9): 1) the sensor memory was erased to avoid any ambiguity caused by the last recording; 2) the threshold, sampling frequency and system time of the sensor are updated based on the user's setting; 3) the sensor is changed to sampling mode and triggered to sample after being disconnected from the PC. After finishing the data collection, the raw data can be downloaded to the PC and be processed and displayed. Operations to the sensor are achieved by sending corresponding commands to the sensor.

The program can plot the Velocity Change (VC) versus peakG and the time sequence of the summation acceleration and the acceleration of each single axis. Before plotting the data on the program, the raw data need to be converted to real acceleration. The conversion of each axis is achieved based on equation 2.1.

$$\mathrm{Acceleration(g)} = ((\mathrm{digital\,count} - \mathrm{zero\,offset}) \times 3000\mathrm{mV}/1023)/6.5(\mathrm{mV}/\mathrm{g}) \qquad (2.1)$$

Where the zero offset is the digital count recorded when the measured axis is under zero acceleration (placed horizontally). The summation acceleration was the scalar of the acceleration vector which is calculated through equation 2.2.

$$\mathrm{Summation} = \sqrt{\mathrm{X}^2 + \mathrm{Y}^2 + \mathrm{Z}^2} \qquad (2.2)$$

The video analysis subprogram (Figure 2.8) consists of three parts, a video player that can display and control the video, an overall impact plot to show all the impacts in one plot and a single impact plot to display the details of the current impact. The cursor in the overall impact plot is used to indicate the current impact and can move according to the display of the video. The subprogram uses relative time to link the video and the impact data so the time of the video camera and of the sensor is not necessarily need to be synchronized in advance. To get the relative time, the user first need to specify a reference time for the video and impact data by selecting the absolute times when the first impact appears in the video and in the impact data which can be achieved by dragging the cursor or the video process bar to the desired place. The program then calculates the relative time of the current video frame to the reference time. Finally, the absolute time of the cursor in the overall impact plot was updated by adding the relative time of the video to the absolute time of the time reference for the impact data (Figure 2.9).

2.4 Calibration and Characterization

2.4.1 Sensor Calibration

In order to get a higher range of reference acceleration, the sensor was calibrated using a centrifuge (Centrifuge 5430R, Eppendorf, Hamburg, Germany) based on the procedure described by Yu et al. [21]. Eight rotational speeds (690, 970, 1190, 1370, 1540, 1680, 1820 and 1940 RPM) were used to create eight acceleration values of 25.21 g, 49.82 g, 74.98 g, 99.37 g, 125.57 g, 149.43 g, 175.38 g and 199.27 g. The speed of the centrifuge was changed from the lowest to the highest rotational speed. The sensor was set to sample with a threshold of 18 g at the sampling frequency of 10 Hz to avoid memory overflow during the calibration. Each rotational speed was kept for several seconds to allow the sensor to record enough samples and the mean summation acceleration of 40 samples was used as one replicate. After the centrifuge reached 1940 RPM rotation speed, the centrifuge was slowed down to the lowest rotational speed. This up and down cycle was repeated four times (2.10). In total, there are 5 replicates for 690 RPM, 4 replicates for 1940 RPM and 8 replicates for 970, 1190, 1370, 1540, 1680 and 1820 RPM. A linear regression analysis between the acceleration provided by the centrifuge and the acceleration recorded by the sensor was performed using MATLAB R2013b (MathWorks, Inc., Natick, Massachusetts, USA). The result (Figure 2.11) showed a linear relationship between the centrifuge and the sensor with coefficient of determination (R^2) of 0.99 and root mean square error of prediction (RMSEP) of 1.249 g. The best-fit line equation was used to calibrate BIRD II.

The precision of the sensor is defined by the standard deviation of the value after calibration (Figure 2.12.a), which is between 0.20 g (at 25.21 g) and 0.81 g (at 125.57 g). The accuracy of the sensor is defined as the deviation of the measured value after the best-fit equation from the centrifuge acceleration values (Figure 2.12.b), which varies between -1.76 g (at 125.579 g) and 2.17 g (at 199.27 g).

The calibration results showed that BIRD II has better precision than BIRD I whose precision is between 0.3204 g (at 149.511 g) to 3.11 g (at 200.793 g) [21]. The increase of precision in BIRD II is largely because of the increase of the sensitivity of the accelerometer due to the reduction in the sensing range. The accuracy of BIRD II is limited from -1.76 g to 2.17 g which is similar to the accuracy of BIRD I (-1.62 g to 2.60 g).

2.4.2 Surface Property Test

To compare surface properties of the blueberry and BIRD sensors, the compression force at 1 mm deformation was measured for both BIRD I and BIRD II using a texture analyzer (TA XT2i, Stable Micro Systems LTD., Godalming, UK) and compared with the data from blueberry fruit. BIRD II was fixed on the base of the texture analyzer using a spherical sample holder. A cylinder probe was used to compress BIRD II by 1 mm and the compression force was measured. Average value was used by measuring six different locations, namely, 4 points at the quartiles of the equator and 2 points at two poles (Figure 2.13). The same test was performed for BIRD I. The results (Table 2.4) showed that smaller force was required for BIRD II (5.54 N) than BIRD I (26.56 N), indicating that the surface property of BIRD II is softer than BIRD I. Compared to the results measured by Robert et al. for blueberries of multiple cultivars under the same condition, both BIRD I and BIRD

II showed higher values (or higher firmness) than blueberry fruit (1.37 - 1.86 N) [23]. Therefore, the BIRD sensors may record higher impact than what a blueberry may experience. It is also noteworthy that the compression force at different test points for both BIRD sensors are different, indicating that the BIRD sensors are not homogeneous, which can be a factor that contributes to the variance of the sensor measurements as discussed in the next section.

Table 2.4. Compression force (N) required for 1 mm deformation of BIRD I and BIRD II at six measured points.

Sensor	T	B	M1	M2	M3	M4	Mean	Std.
BIRD I	17.81	30.43	30.66	25.30	23.93	31.21	26.56	4.81
BIRD II	4.87	5.31	6.60	5.17	5.74	5.52	5.54	0.55

2.4.3 Dynamic Drop Test

In order to evaluate the performance of BIRD II and compare it with BIRD I, dynamic drop tests of both BIRD I and BIRD II were conducted. Both the sensors were dropped from five drop heights of 2.5, 5, 7.5, 10 and 12.5 cm with 40 replicates for each drop height. A 1.2 cm padding sheet (Poron ”No-Bruise”, A & B Packing Equipment Inc., Lawrence, Michigan, USA) and a 0.2 cm steel sheet were selected as the contact materials for their different surface property. The steel is hard material (higher elastic moduli) with little energy absorption and commonly used in machines while the padding sheet has strong cushioning effect that can absorb more energy. Mean and standard deviation of the peakG and VC are used in the data analysis. Although there were several impacts (bounces) at each drop, only the first impact of each drop was considered. Theoretically, the same sensor should record different response on different contact materials and BIRD I and BIRD II should have different response for a given contact material due to the different housing materials.

The standard deviation of the peakG (Figure 2.15.a) measured by BIRD II were smaller than that measured by BIRD I for all drop heights on both steel and padding sheet although the standard deviation varied over different drop heights. For BIRD II, the peakG measured on the padding sheet and steel surface had standard deviations ranging from 0.64 to 1.91 g and from 3.52 to 5.95 g, respectively; For BIRD I, the peakG measured on the padding sheet and steel surface had standard deviations ranging from 1.31 to 2.58 g and from 9.11 to 55.68 g, respectively. BIRD II had smaller standard deviation in VC than BIRD I for all drop heights on the padding sheet and for all drop heights except 2.5 cm on the steel surface (Figure 2.15.b). Overall, BIRD II had smaller variance in measuring dynamic impacts than BIRD I.

For both the sensors, the standard deviations of the peakG and VC measured on the padding sheet were smaller than on the steel surface for all the heights. Possible reason could be that the cushioning provided by the padding sheet reduced the difference caused by the inhomogeneous of the sensor, while the steel tended to increase the difference due to its hard surface.

For the same drop height, the mean peakG values measured by BIRD II on the steel surface were smaller than those measured by BIRD I (Figure 2.15). No significant difference was found on the padding sheet which may be due to the cushioning of the padding sheet that reduced the response difference between BIRD I and BIRD II. Both the sensors recorded higher mean peakG on the steel than on the padding sheet, which was consistent with the texture of the contact material. Linear relationships between the mean peakG and drop height were observed for BIRD I and BIRD II with a coefficient of determination (R^2) of 0.989 and 0.985 for the steel surface, and of 0.994 and 0.998 for the padding sheet, respectively.

2.4.4 Sensor Surface Uniformity Test

The variance of the IS measurements is mainly contributed by two sources - the precision of the sensing unit (e.g. accelerometer, pressure sensor) and the inhomogeneity of the IS. Essentially, any inconsistency (e.g. uneven thickness, flat spot and irregular shape) in the IS will affect the reading [10]. For example, the pressure measured by the Pressure Measuring Sphere (PMS60) spreads by 13.8% at different orientations given the same static pressure [16]. The potato-shaped instrumented device (PTR 200) also measures significant different values between different impact zones given the same impact force under the pendulum test [24].

To have an overall view of how BIRD II responds at different collision points, uniformity test was performed using a pendulum. BIRD II was attached to one end of the pendulum (Figure 2.16) to fix the collision point and was released to collide with the contact material against a rigid vertical wall. The same six points used for the texture analyzer (Figure 2.13) were chosen as collision points. The same contact materials (padding sheet and steel) used in the dynamic drop test were tested. Each collision point was tested 30 times and only the first impact of each drop was used for analysis. ANOVA test was performed on peakG value to test whether there were statistic differences between the impact values from the 6 points.

As shown in Figure 2.17, the sensor recorded different peakG values at different collision points. ANOVA test showed that there was significant difference (p value ¡0.0001) between different collision points. The different responses of the sensor over different collision points contribute to the variance of the measurements under the dynamic impact. It was also observed that the variance among the six collision points on the padding surface (3.144 g) was less than on the the steel surface (44.995 g), suggesting that the mechanical properties of the contact surface also affects the variance of the sensor measurement.

The variation of the six collision points of BIRD II could be caused by several factors, such as the shape of the housing mold not being perfect spherical, the accelerometer, circuit board and battery not being positioned in the center and the air bubbles in the housing material. These factors are introduced in the housing process and usually sensor-dependent. It is a challenge to make the sensor surface uniform mainly because it is difficult to keep the thickness of the cast material around the sphere uniform as limited by the small size of the sensor. To address this issue, it is necessary to have adequate replicates to minimize the uncertainty of the measured mean value when the BIRD sensor is used in the field.

2.5 Conclusions

Compared to BIRD I, BIRD II is 17% smaller in diater and 51% lighter in weight. The performance of BIRD II consistently surpasses that of BIRD I in terms of sensitivity, precision, memory capacity, cost, and ease of use. BIRD II gives a more accurate approximation to a berry fruit compared to BIRD I. However, challenges still remain in making the surface texture property of the BIRD sensor more similar to fruit texture, as well as in improving the surface uniformity of the sensor.

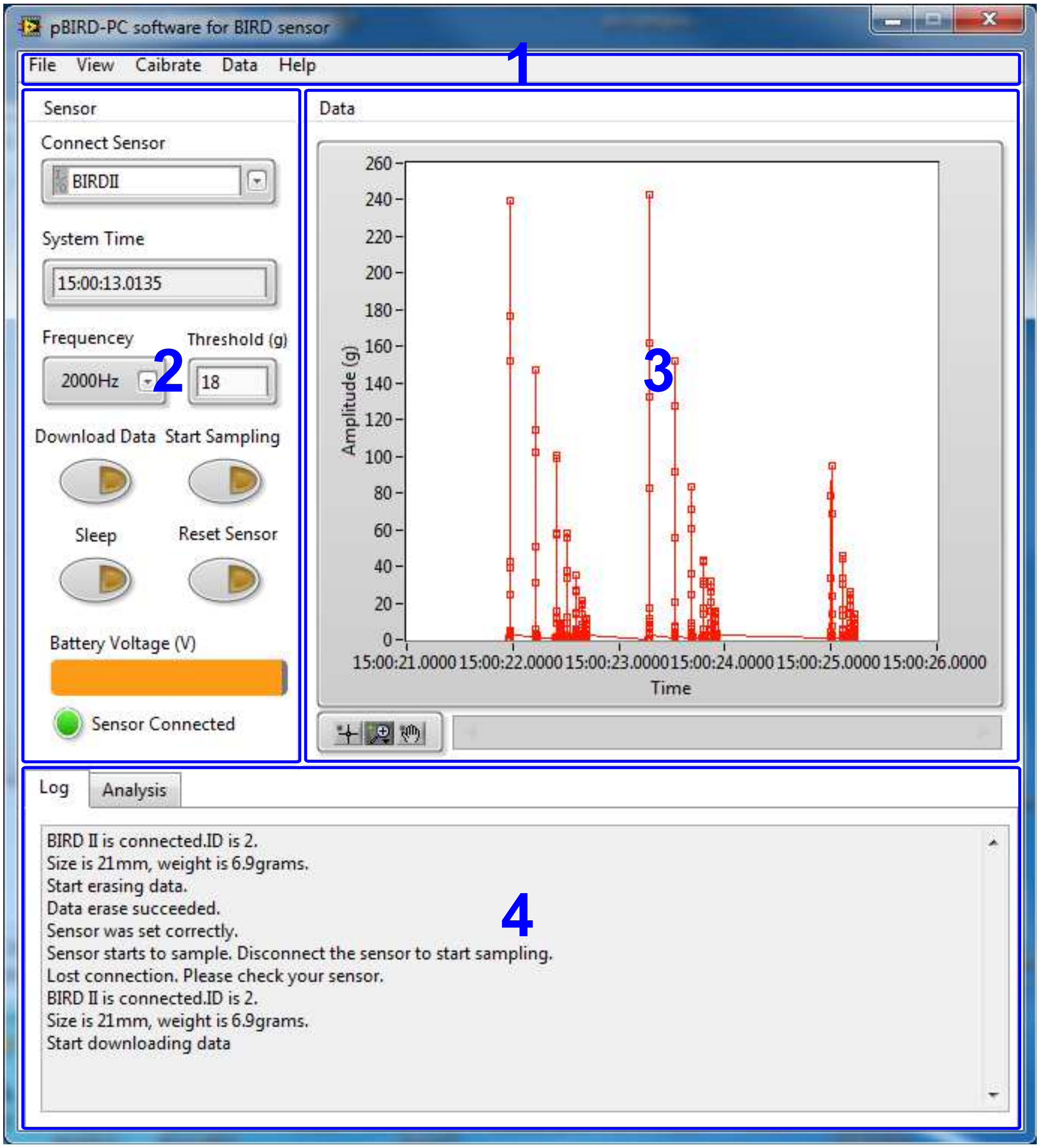


Figure 2.7. Front panel of the main PC program. 1: Menu bar. 2: Sensor configuration. 3: Data visualization. 4: Operation history.

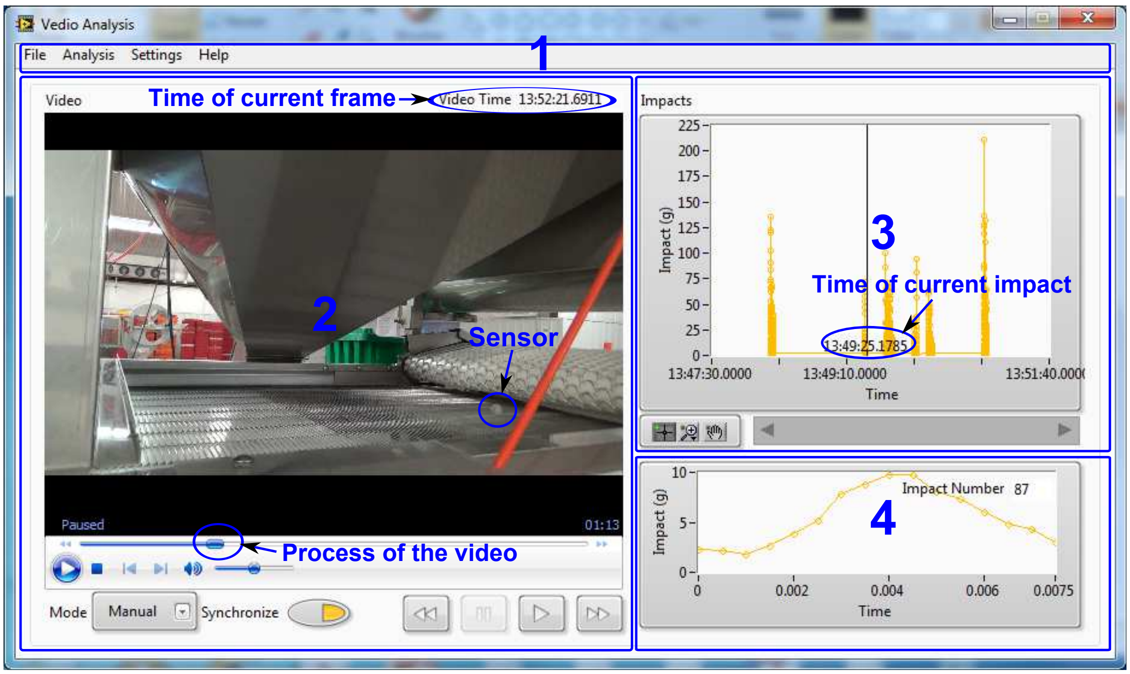


Figure 2.8. Front panel of the video analysis sub program. 1: Menu bar 2: Video display and control. 3: Overall Impacts display. 4: Single impact display. The video and impact data come from a field test on a blueberry packing line. It clearly shows the impacts near the cursor occurred when the sensor was transferred from the white conveyor belt to the steel conveyor belt. The program uses relative time to synchronize the display between the video and impacts even their absolute time is different.

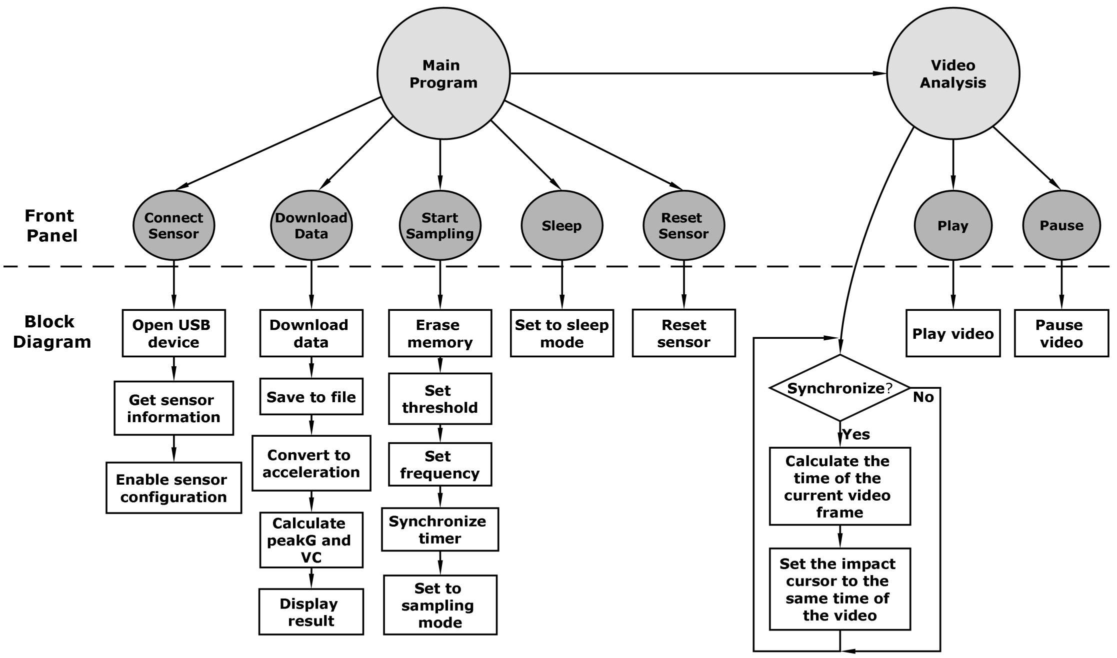


Figure 2.9. Schematic of the PC program. The block diagram implements the functions of the button in the front panel.

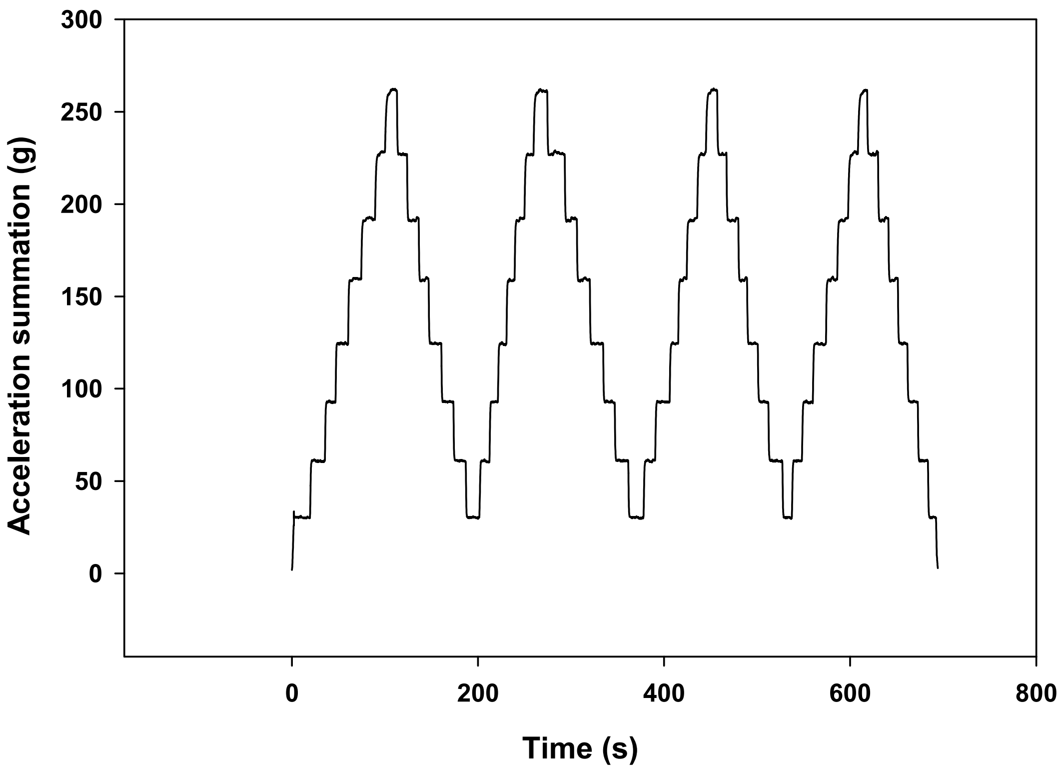


Figure 2.10. Raw acceleration recorded by the BIRD I during calibration. g=9.8 m/s^2

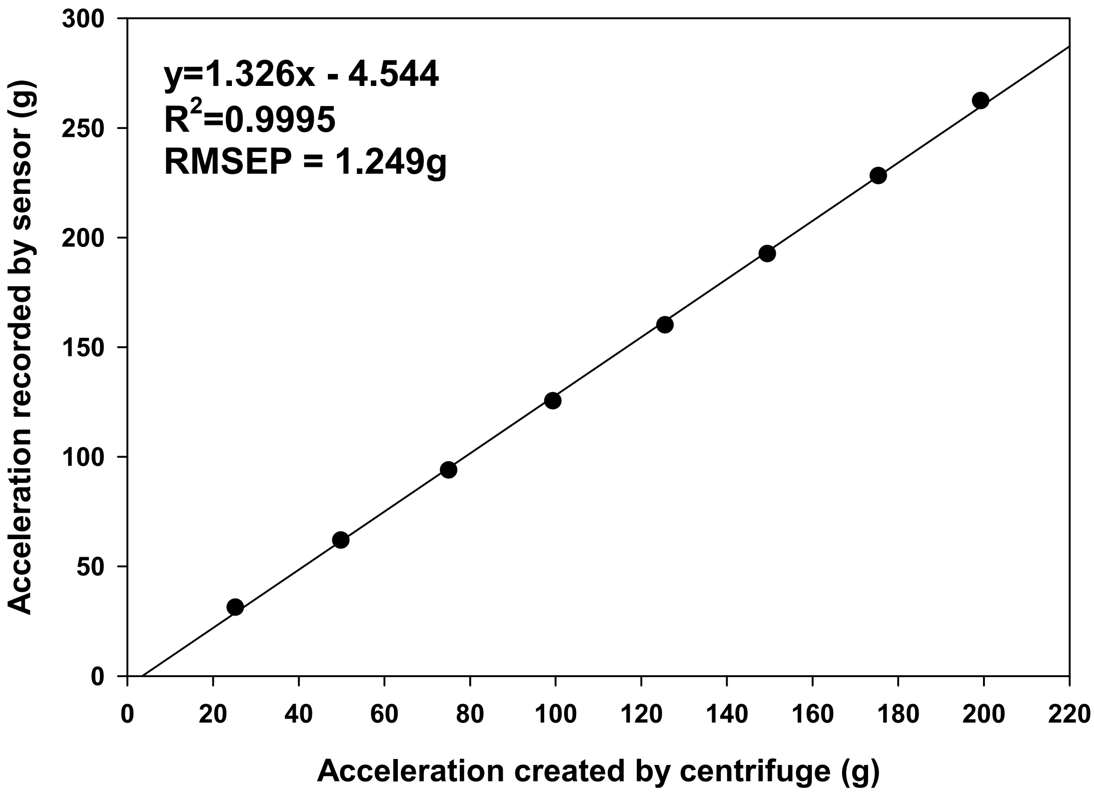


Figure 2.11. Linear relationship between the acceleration provide by the centrifuge and the values recorded by the sensor. g=9.8 m/s^2

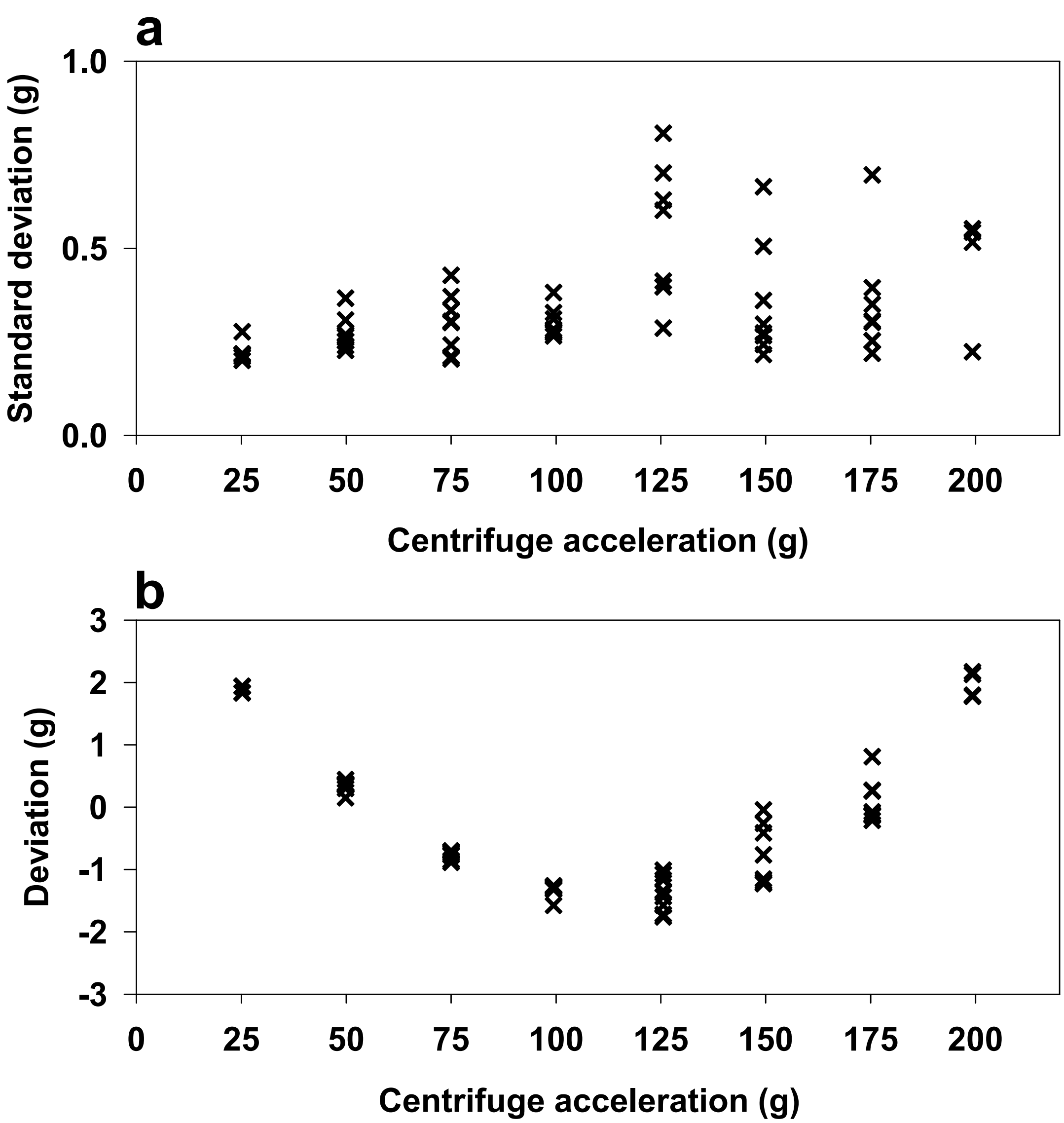


Figure 2.12. BIRD II calibration: standard deviations at the eight acceleration values (a) and deviation of the acceleration values measured by BIRD II from the centrifuge acceleration values (b). g=9.8 m/s^2

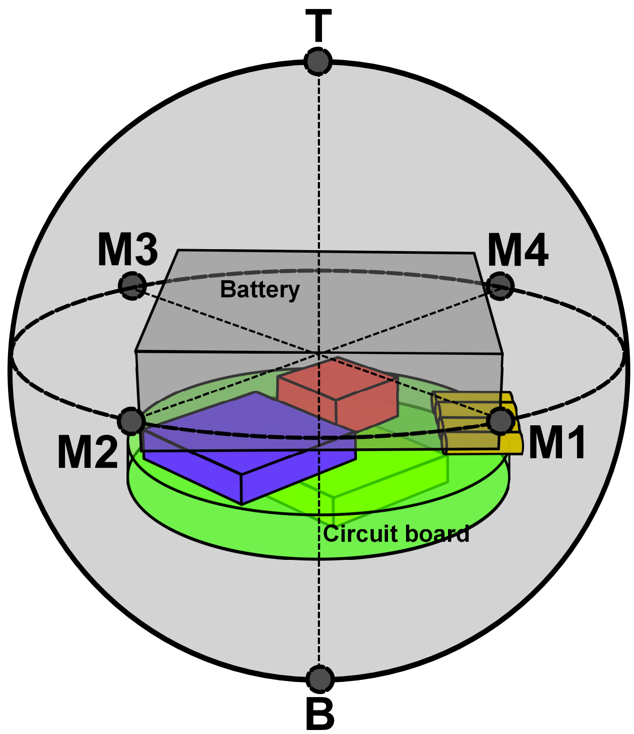


Figure 2.13. Schematic of the location of the six measured points.

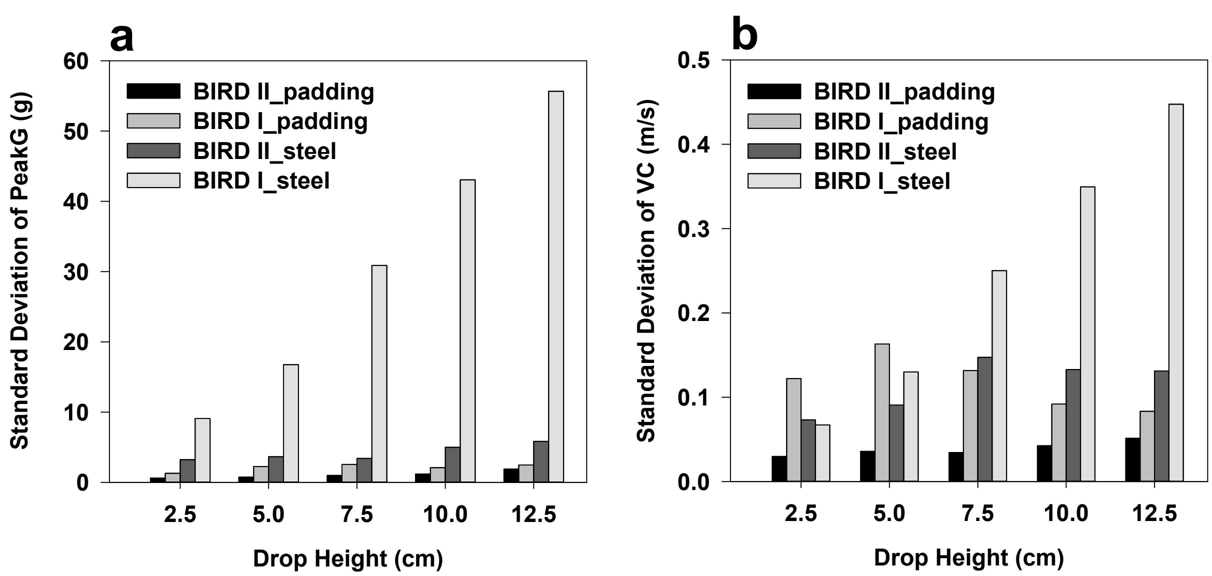


Figure 2.14. Variance in the dynamic drop measurements from BIRD I and BIRD II. Standard deviation of peakG (a) and standard deviation of VC (b).

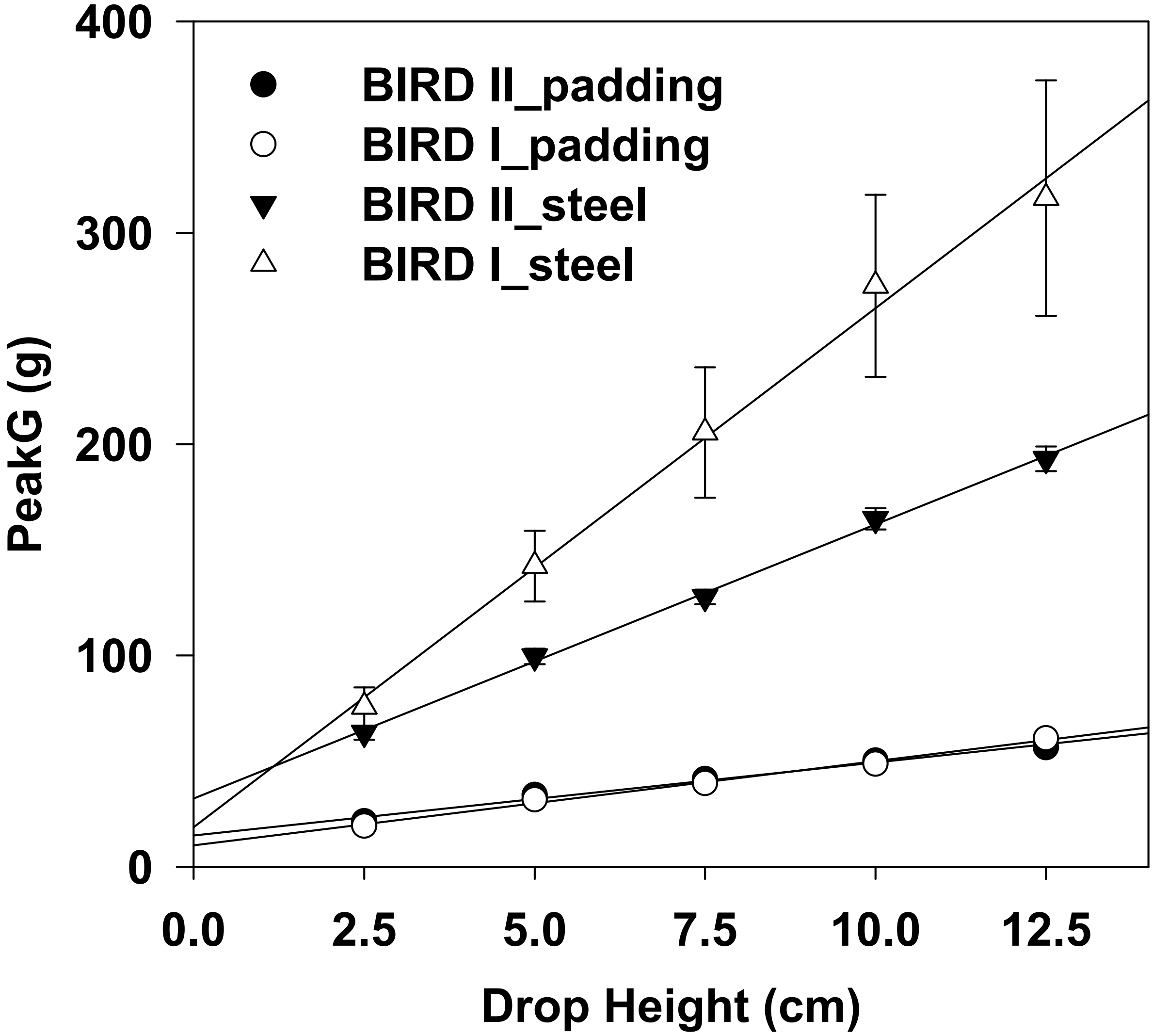


Figure 2.15. Mean peakG measured by BIRD I and II at different drop heights on two contacting materials.

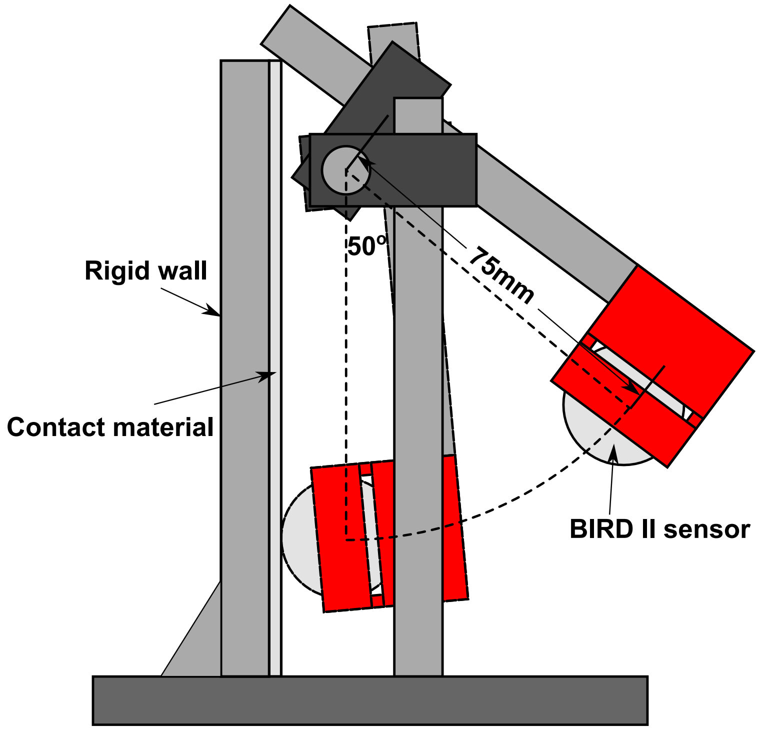


Figure 2.16. Schematic of the pendulum test (side view).

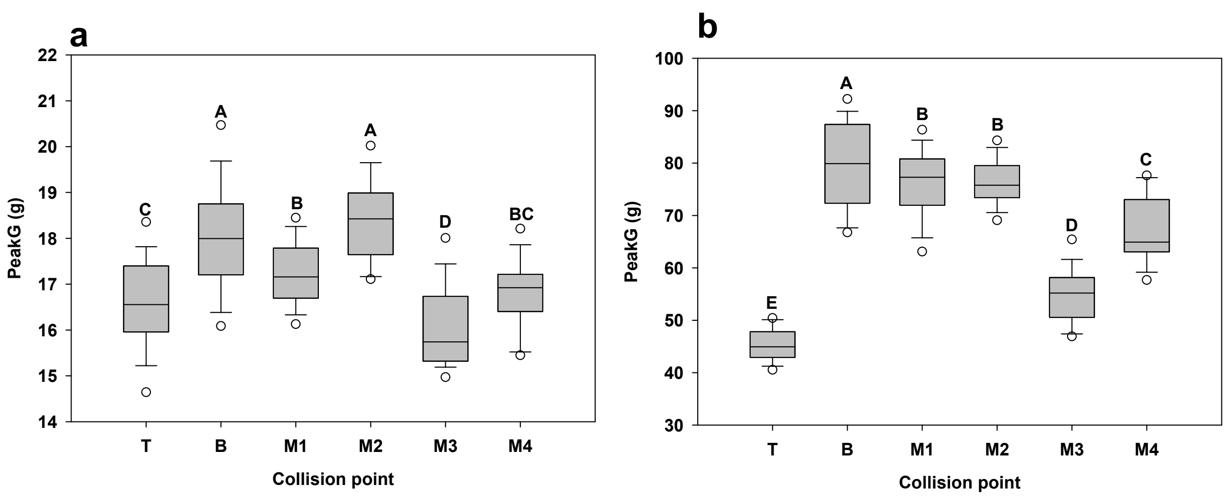


Figure 2.17. Uniformity test results for padding sheet (a) and steel (b). The collision points with the same letter indicate there was no significant difference between them.

CHAPTER 3

EVALUATING BLUEBERRY PACKING LINES USING THE BERRY IMPACT RECORDING DEVICES[1]

[1] R. Xu, C. Li, F. Takeda, G. Krewer. To be submitted to *Transaction of the ASABE*.

3.1 Introduction

Blueberry is the second most important berry crop in the United States, producing 850 million dollars value in 2012 [1]. The United States is the largest producer of blueberries in the world, harvesting a total of 564.4 million pounds of cultivated and wild blueberries in 2012 [25]. Mechanization of blueberries was used in harvesting and post-harvest handling to increase the production efficiency and reduce the labor cost. However, mechanization of blueberries also causes bruises in blueberries due to mechanical impacts during the harvesting, transportation, and packing when fruits collide with hard surface, reducing the fruit quality and shelf life. In the process of handling blueberries from filed to the market, machine harvesters and packing lines are the two main sources that produce large mechanical impacts to blueberries. Brown et al. estimated that 78% of the blueberries were bruised during the harvesting process using a commercial machine harvester [7]. In addition he reported that the blueberries could have bruise rates from 0 to 50% from 150 to 300 mm drop height on a hard surface which has been observed on many packing lines. Therefore, there are high probability the blueberries can be damaged by the packing lines, however, these potential damage has not been studied so far.

Previous studies on evaluating fruit packing lines focused on quantifying the impacts using Instrument Sphere (IS). In essence, an instrumented sphere is a data logger that mimics the mechanical behavior of a fruit when it is subjected to the same mechanical stress as a fruit. Therefore, the IS can provide quantitative information of the impacts created by the packing lines, helping researchers quickly evaluate and compare the impact damage between different lines and different settings. PeakG and Velocity Change (VC) are two parameters that can be used to establish the relationship between the impact value measured by the IS and the fruit bruising rate in order to estimate the actual bruise potential [26, 27]. Brown el at. developed a method to classify surfaces based on the VC vs. peakG graph [9]. This method can be used to identify cushioned or hard surfaces used in handling systems as equivalent of known surfaces.

Various ISs have been developed and used to evaluate commercial packing lines. A number of studies used an instrumented sphere designed by USDA-ARS/Michigan State University to evaluate the packing line for varies fruits and vegetables[19]. Researchers ran the IS on the packing lines to record the impacts along with a video camera to record where the impact happened. The recorded impacts could be directly correlated to fruit bruising rate or compared with the surfaces with known relationship between impacts and bruising rate. Brown et al. used the instrumented sphere to evaluate and identify the location of the impacts on 25 commercial apple packing lines [9]. Comparing the impacts recorded by the IS with the fruit bruising data after running apples through the lines, they found high correlation between the summation of all peakG of the impacts exceeding 20 g with the total bruise damage and both of them were reduced by making appropriate line changes. They also suggested to avoid high elevation change and hard contact surface. Mathew et al. tested two potato packing lines using the same IS and they found high impacts at many transfer points on both lines [10]. Although the relationship between the impacts and potato tube bruising rate was not identified, they compared the impacts with known surfaces and found impacts on hard surfaces were numerous. Timm et al. identified several transfer points that cause high impacts on eight commercial onion packing lines and many of the impacts are classified as high level using the peakG vs. VC plot of standard surfaces [28]. The relationship between the impact and onion bruising rate was also established in this study.

To our knowledge, no study has reported on evaluating the commercial packing lines for blueberries because no small IS has been available to resemble small fruit like blueberries. For example, the IS used in the mentioned studies has 89 mm in diameter which is much larger than a typical blueberry (7 mm to 23 mm in diameter). Therefore, it cannot be used to evaluate the blueberry packing line. Our research group developed a miniature IS for small fruits, known as Berry Impact Recording Device (BIRD) [21, 22]. The sensor has three single axis accelerometers to measure the acceleration of three orthogonal axes at a maximum sampling frequency of 3 KHz and each axis has a sensing range of $\pm$ 500 g (g = 9.8 m/s^2). The sampling frequency and sensing range are adequate to measure the impacts during the packing lines, given the drop heights of each transfer point between 10 cm to 40 cm. The size of the sensor is 25.4 mm in diameter which provides a close approximation to a real blueberry. A second generation of BIRD (BIRD II) sensor was developed recently with smaller size (21 mm in diameter) and less weight (6.9 gram), making the sensor a better approximation to a real blueberry. The primary objectives of this study were to test 11 commercial blueberry packing lines and quantify the impacts during the blueberry packing process. Specific objectives were to 1) quantify the impacts created by each packing line, 2) quantify the impacts created by each transfer point, 3) find and test a padding sheet for the packing line and 4) estimate the fruit bruising caused by the impacts recorded using peakG vs. VC plot.

3.2 Material and Method

3.2.1 BIRD Sensors

The BIRD sensor is a miniature instrumented sphere designed for small fruits and vegetables. The first generation of BIRD (BIRD I) sensor was designed to record the time and x, y and z acceleration of impact events using three single-axis accelerometers. Its miniature size (25.4 mm in diameter) and weight (14 grams) allows the BIRD I sensor to go through the packing line in a way that is similar to a real blueberry [21]. Its sensing range is 500 g (1 g = 9.8 m/s^2) for each axis, which is adequate to record most of the impacts occurred in packing lines. An interface box is used to connect the sensor with PC and serves as an intermediate device which can store the sensor data and charge the sensor. A LabVIEW (National Instruments, Austin, Texas, USA) based software ”iBIRD” was designed to configure the sensor, download data from interface box, process raw data and graphically display the results [22]. The software calculates the ”peakG” by finding the largest acceleration (g value) within one impact curve and ”Velocity Change (VC)” by integrating the impact curve over time. For all field tests in this study, one fully calibrated sensor was used.

The second generation BIRD (BIRD II) sensor is an improved version of the first generation. Compared to the first generation, the size of BIRD II was reduce to 21 mm in diameter and the weight were reduced to 6.9 gram. These improvements were achieved by reducing the size of the circuit board and battery, making the sensor closer to the size and weight of a typical blueberry. Its sensing range was reduced from 500 g to 200 g (1 g = 9.8 m/s^2) for each axis, but the precision was increased as a result. The BIRD II also used soft housing material so the amplitude recorded by BIRD II is smaller than BIRD I. Preliminary test on blueberry packing line showed that most of the impacts are less than 200 g, so the sensing range of BIRD II is larger enough for evaluating the packing line.

3.2.2 Blueberry Packing Line

Over the past two years, 10 commercial blueberry packing lines were evaluated using the BIRD I sensor. Two packing lines with blueberries in Georgia in June 2013, four empty packing lines in Michigan in August 2013 and four empty packing lines in North Carolina in May 2014 were tested using BIRD I sensor. After the BIRD II sensor was developed and calibrated, one additional packing line in Florida was tested using BIRD II sensor in April 2014. In order to identify and test a padding sheet for the packing line, the same packing line in Florida was tested using the BIRD II sensor after padding some critical transfer points. The information of each line was summarized in table 3.1.

Table 3.1. Summary of packing lines.

Line Number	Location	Time	Sensor	Replicates	Transfers	W/O Fruit
1	GA	June, 2013	BIRD I	5	6	W
2	GA	June, 2013	BIRD I	5	7	W
3	MI	August, 2013	BIRD I	4	4	O
4	MI	August, 2013	BIRD I	6	4	O
5	MI	August, 2013	BIRD I	6	4	O
6	MI	August, 2013	BIRD I	5	5	O
7	NC	May, 2014	BIRD I	6	7	O
8	NC	May, 2014	BIRD I	6	6	O
9	NC	May, 2014	BIRD I	6	6	O
10	NC	May, 2014	BIRD I	6	7	O
11	FL	April, 2014	BIRD II	6	7	O

Simple surveys of the packing lines were completed by placing the BIRD I or BIRD II sensor gently at the beginning of each line and collect the sensor at the end of the line, allowing the sensor to record the impacts at each transfer (point where of drop or roll occurred during transfer from form one operation to the next). Based on the preliminary tests, bother the BIRD I and BIRD II sensor were set to record impacts larger than 25 g (to avoid trivial impacts) at a frequency of 2 KHz. Each packing line was tested at least 4 times in order to obtain get a reasonable estimation of the impact damage.

A typical commercial blueberry packing line has five main types of line components: blower, color sorter, soft-fruit sorter, clamshell filler and conveyor belts (including inspection table) that connect each component (Figure 3.1). Different combination and alignment of these components forms different lines with different number of transfer points. The specific structure of the tested lines are shown in Figure 3.2. Typically, blueberries are dumped at the beginning of the packing line and then conveyed to the wind blower through a lifting conveyor. The wind blower can blow out light blueberries, leaves, and other trash. The conveyor belt for the wind blower is usually made of steel with holes that allow small objects to go through. A strong squirrel cage fan at the end provides the final cleaning. Because of the wind from the blower, the blueberries could bounce several times and impacts will occur in this section. However, the BIRD sensors may not record any impacts because of their large weight keeps it on the conveyor. After the wind blower, the blueberries will go through the color sorter and soft sorter, to remove immature and soft fruit. A line can have multiple color sorters or soft-fruit sorters and the color sorter and soft sorter can use same conveyor. After the color sorter or soft-fruit sorter, the blueberries are inspected manually at the inspection table. The blueberries then transfer through one or multiple conveyors before they are transferred to the clamshell filler which usually has a hopper to temperately store the fruits.

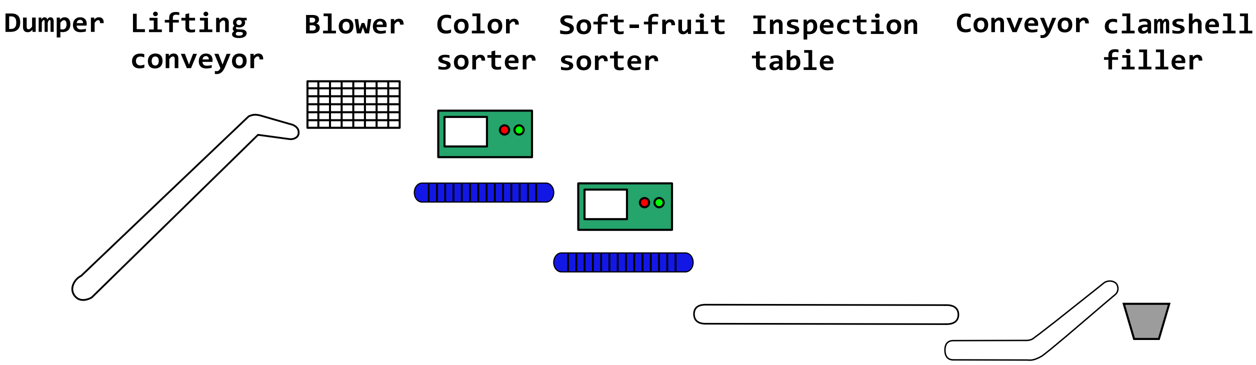


Figure 3.1. Schematic of a typical blueberry packing line.

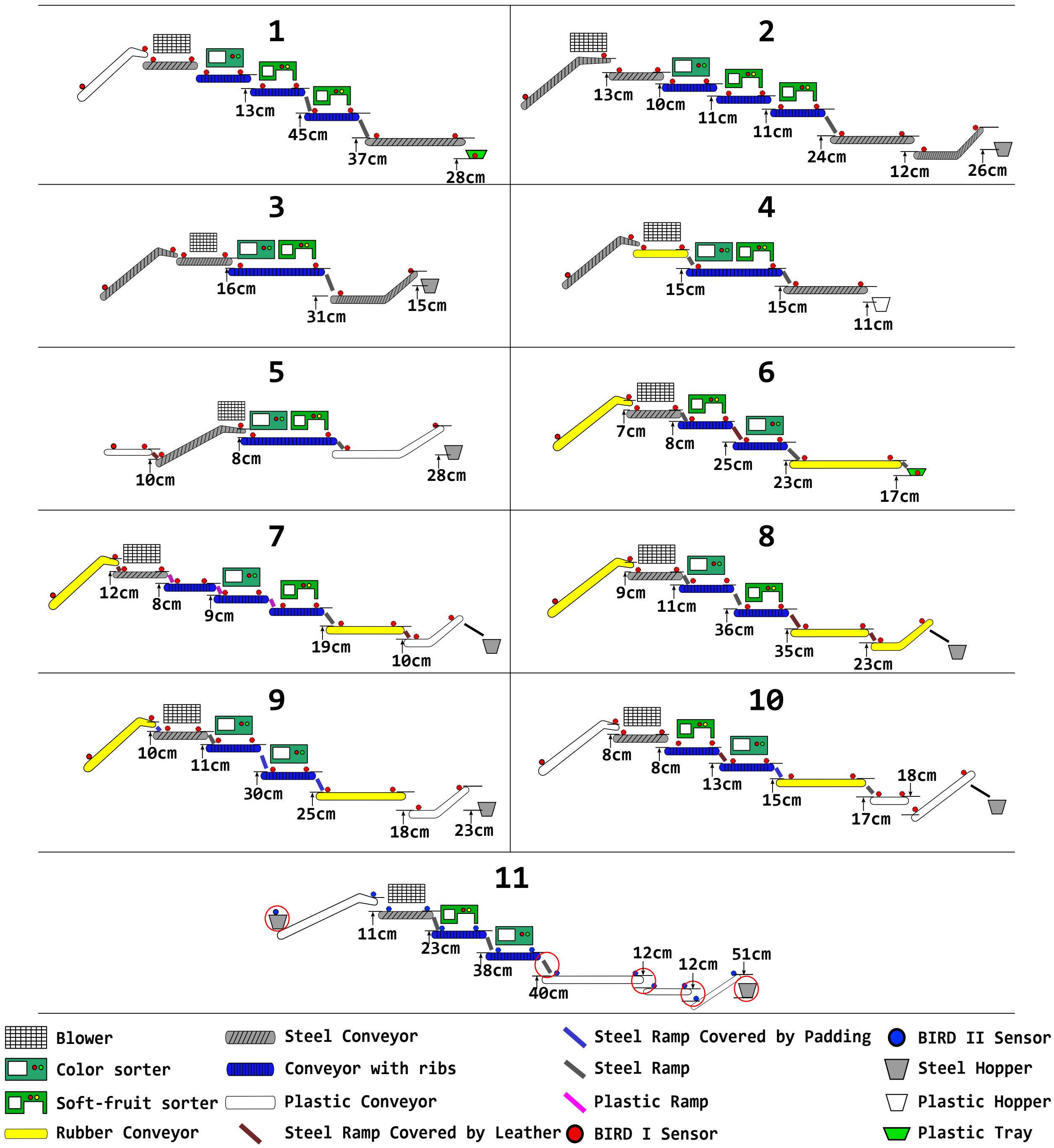


Figure 3.2. Schematic for the tested 11 packing lines by BIRD I and BIRD II sensor. The drop height for certain transfer points are missed due to the difficulty of measuring the height. The red circles indicate the padded transfer points.

3.2.3 Padding Sheet and Line Modification

Line 11 was first tested using BIRD II and after checking the data recorded by the sensor on the empty line, 4 transfer points (circled in Figure 3.2) were identified as critical points which produced the large impacts. These transfer points were padded using water-proof padding sheet (Poron ”No-Bruise”, A & B Packing Equipment Inc.) to reduce the impacts. Only one side of the hopper was covered by the padding sheet. After modification, the packing line was tested 6 times using the same sensor with the same procedure described above. Using the 6 replicates, the average impact level (average, maximum and cumulated peakG) was calculated for each transition point.

3.2.4 Video Recording

A video camera (HDR-CX380, Sony) with 60 frames per second was used to record and track the motion of the BIRD sensors. Before each test, the time of the video camera was synchronized with the PC timer, which was also synchronized with the sensor time. The video camera followed the movement of the sensor and kept the sensor within the view of the camera especially at the transfer points. However, due to the fast speed of the conveyor belts (e.g. conveyor belts of the color sorter and soft-fruit sorter), the movements of the sensor at some transfer points were not recorded by the video. Therefore, the time of the sensor dropped at each transfer point was also recorded manually using a timer. The videos successfully differentiated the sensor from fruits and mechanical parts.

3.2.5 Data processing and Analyzing

The raw data recorded by BIRD I and BIRD II were processed in MATLAB R2013b (MathWorks, Inc., Natick, Massachusetts, USA). Each replicate was first separated into single sections which only contained the impacts at each transfer point. Then the average impact level (average, maximum and cumulative peakG) at each transfer point were calculated and summarized. The average impact level for each packing line was also calculated. The maximum peakG relates to the maximum damage to the fruit and the cumulative peakG reflects the cumulative damage by several impacts. Mean separation was performed on the impact level to classify the packing lines into groups. The velocity change reflected the hardness of the contact material. In general, soft material (e.g. cushion) has larger VC and smaller peakG compared to hard material (e.g. steel) if the sensor was dropped from the same height onto them. For line 11, t test was performed to compare the impact level of the transfer points before and after padding them.

In order to accurately synchronize the video with the impacts recorded by the sensor, a LabVIEW based program was designed to align the video display with the impact data. There are two panels to in the program: one is used to display the video; the other one graphs the impact data and a cursor was used to indicate the current time of impact data. Users first manually aligns the cursor with the first impact in the data file and the first impact occurred in the video, and then the program will automatically move the cursor as the video plays so the user can associate the impact with the location of the sensor.

3.3 Results and Discussion

3.3.1 BIRD Sensor Reading

Although the amplitude recorded by BIRD I and BIRD II are not comparable because of the different surface property of the casting material, the plot of impact over time recorded by the two sensor are similar. Both the BIRD sensors recorded impacts larger than 25 g and most of the impacts occurred at transfer points (Figure 3.3). Video record showed a few impacts occurred when the sensor hit on the sidewall of the conveyor belts. However, these impacts were excluded from the data analysis since they were insignificant and rarely happened in normal operation with fruits. At each transfer point, the sensor recorded a large impact at the initial drop which was followed by several small impacts due to the bounce of the sensor. The largest number of impacts were recorded when sensor was transferred to the hopper due to the bounce of the sensor around the steel surfaces. The amplitude of the impacts mainly depends on the drop height of the transfer point, the surface properties of the contact conveyor and the speed of the fruits. Fast speed of the conveyor belt leads to fast moving speed of the fruits at the end of the conveyor, resulting in large impact damage to the fruits when dropped on the following line part. For this particular line, the BIRD I sensor recorded the biggest impact when transferred from color sorter to soft-fruit sorter, which is mainly due to its largest drop heights with the line. The speed of the conveyor belt for color sorter and soft-fruit sorter are normally faster than other conveyor belts within one packing line, which was reflected from the time between two successive big impacts. Therefore, large impacts usually occurs at the transfer points when fruits come out from color sorter and softer sorter.

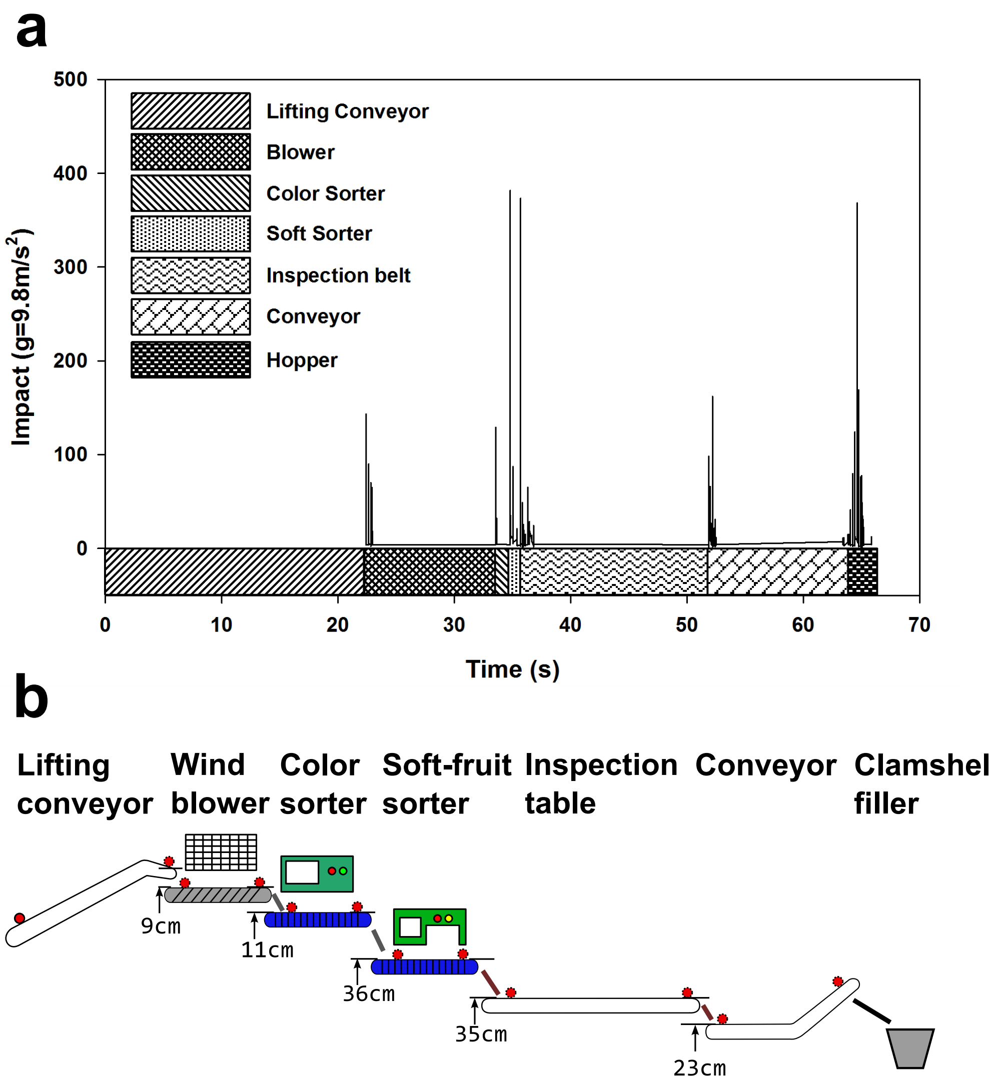


Figure 3.3. Real time response of the BIRD I sensor reading for a single run (a) with the schematic of the measured packing line (b).

3.3.2 Effect of Fruit on the Sensor Reading

The impact level of each line (Figure 3.4) differs due to different alignment and setting of different mechanical components. The blueberries also have effect on the sensor reading since the fruits on the convey belt and hopper could provide cushion for other blueberries and reduce the bouncing of blueberries. For example, the overall impact level recorded on line 1 and 2 which were tested with fruits are the smallest among all the lines. Comparing the last transfer point among all the lines, line 2 has the smallest impact level (Figure 3.5) and number of impact (Figure 3.6). Similarly, Line 1 also showed smaller impact level and number of impact comparing to other lines tested without fruit at the last transfer point. Video revealed that the sensor dropped on top of fruits stacked in the hopper when testing line 1 and 2 while the sensor dropped on the steel directly when testing other empty lines. The difference in the sensor reading on lines with fruits and without fruits shows the real damage that the packing line produced at certain transfer points in normal operation (when there were fruits on the lines) may be smaller than the sensor measured in empty lines. Therefore, the sensor reading on the empty lines gives an estimation of the maximum impact damage for the packing lines. Although the impact level recorded by the sensor on empty lines are larger than the real damage that a fruit experienced in the normal operation, it is reasonable to compare the mechanical damage of the lines using the sensor reading.

3.3.3 Impact Level of Line 1 - 10

There were multiple transfer points on each line and most of impact surface were steel, plastic and rubber. An average peakG of 60 to 111 g, maximum peakG of 129 to 402 g, cumulative peakG of 879 to 3196 g and number of impacts of 15 to 38 were recorded on the 10 lines. Line 1 and 2 had the smallest impact level due to the cushion of the fruit on some transfer points. Among 8 empty lines, line 3 has the smallest average and cumulative peakG and number of impacts and line 4 has the smallest maximum peakG, since line 3 and 4 has only 4 transfer points which are the smallest among all the lines. Line 5 also has 4 transfer points, however, due to the large drop height in the last transfer point, line 5 has the largest maximum peakG. The largest average and cumulative peakG was found in Line 9 because of the large number of transfer points and total elevating height.

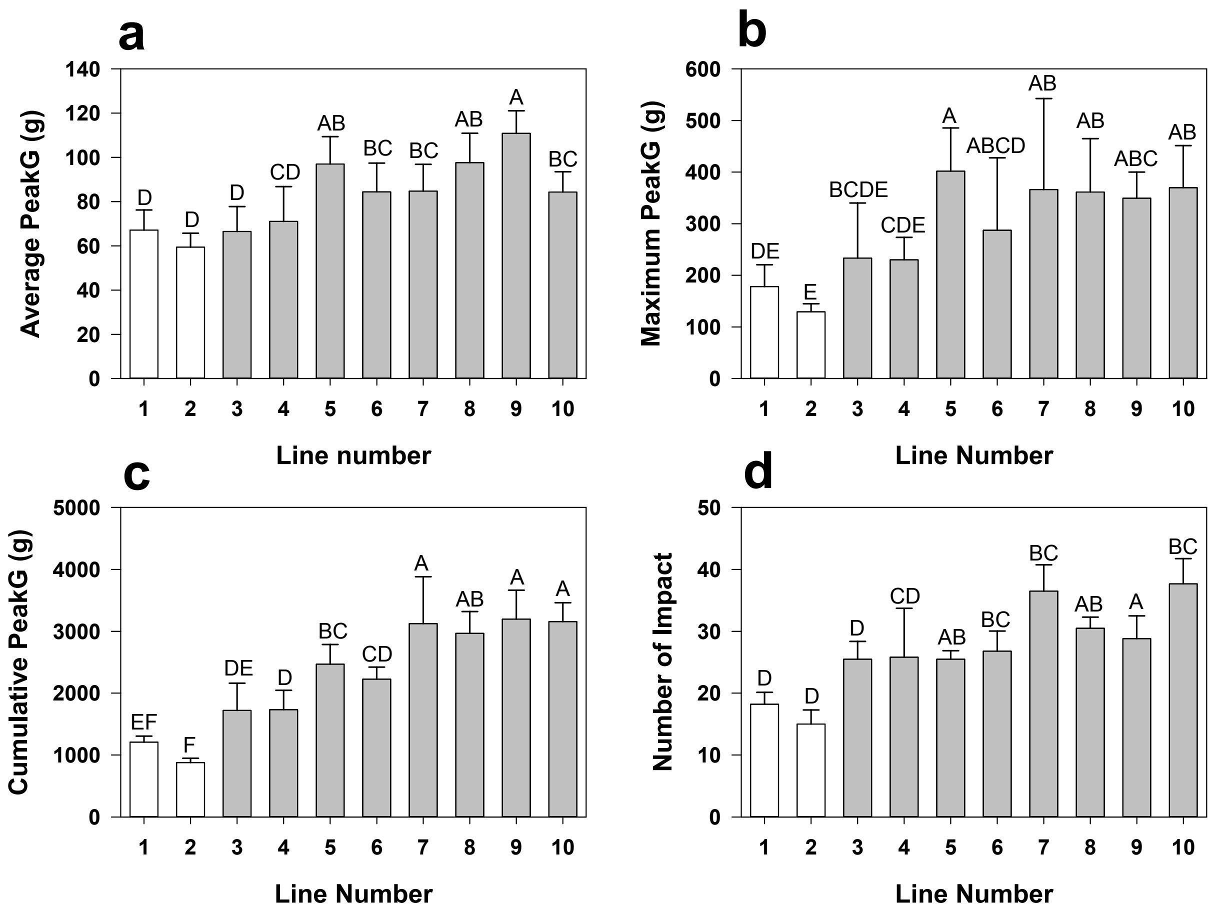


Figure 3.4. Overall impact level for 10 packing lines tested by BIRD I. The white bars indicate the lines that were tested with blueberries. The line with same letter showed no significant difference. g = 9.8 m/s^2.

The impact level on each transfer points are plotted in Figure 3.5. Among all the transfer points of the 8 empty lines, the last transfer point has the largest impact level for most of the lines, which is expected because the sensor dropped into the clamshell filler or tray from a relative high position (15 to 28 cm) and bounce several times within the hopper. Although the blueberries in the hopper can reduce the impacts during normal operation, it is still recommended to cushion the side of the hopper to minimize the impact damage to the fruits.

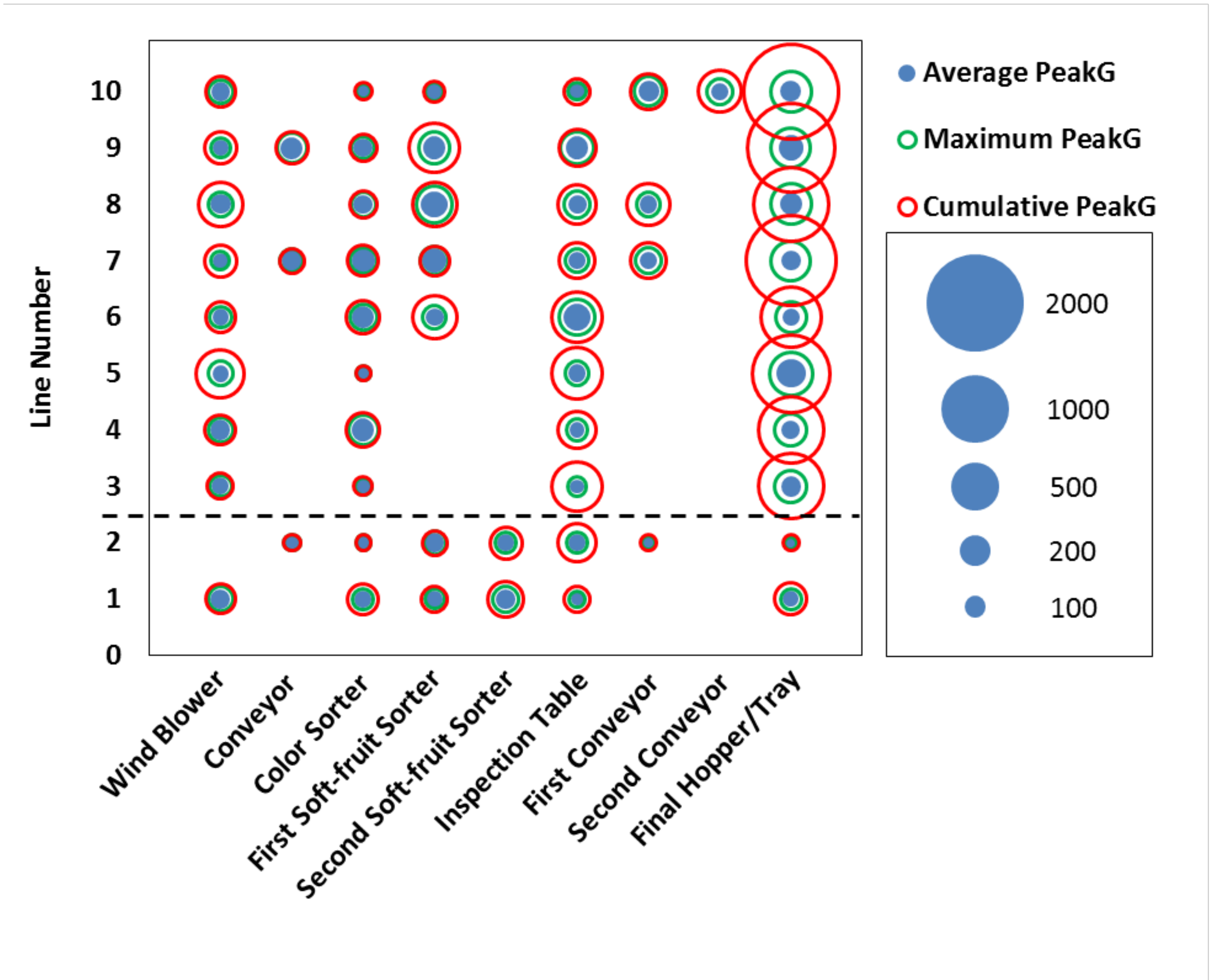


Figure 3.5. Bubble plot of the impact level for the transfer point when transferred onto indicated component. The peakG value is proportional to the area of the circle. The blue, red and black circle presents the average, maximum and cumulative peakG value, respectively. The two packing line under the dash line were tested with blueberries. The right plot shows the reference size with the indicated value. g = 9.8 m/s^2.

Theoretically, the mechanical damage created by the packing line is mainly determined by the drop height at each transfer point, speed of the conveyors and surface properties of the contact material. An ideal packing line with minimum damage should have minimum number of transfer points with minimum drop height at each transfer point and the conveyor belts move at a reasonable speed which is not too slow to effect the packing efficiency or too fast to create large impacts. However, most of the commercial packing lines may not meet all the requirements due to the specific mechanism of the machine. For instance, most of the color sorters or soft-fruit sorters use air pulse, which needs a minimum drop height, to reject the unwanted fruits from the packing line. Typically, in order to reduce the impact damage at transfer points, many commercial lines either reduce the height of the drop or use ramps at transfer points to reduce the speed of the fruits. Line 3, 4 and 5 remove the drop between color sorter and soft sorter by installing them on the same conveyor. In this case, the impact level on the transfer points at the color and soft-fruit sorter in total in line 3, 4 and 5 are smaller than other packing lines. Ramps are found at many transfer points among the tested lines, however, inappropriate installation (e.g. large ramp angle, hard surface) of the ramp may not decrease the velocity at the end of the ramp efficiently, resulting in significant impacts at the end of the ramps [29]. Therefore, additional decelerator are recommended to reduce the speed of the fruits at the end of the ramps. For example, using blanket and curtain can increase the length and friction of the ramp which subsequently decrease the speed. Additional cushion on the ramp can also absorb the energy when the fruits hit on the ramp.

The sensor bounced at each transfer point and recorded several impacts (Figure 3.6). Since the surface properties of the sensor and blueberries are not identical and the sensor can bounce more times than the fruit at certain transfer points, the blueberries may experience less number of impact on the packing line. However, the number of impacts is still an useful index to compare the impact between transfer points and packing lines. The largest number of impact recorded is 20.5 at the last transfer points of line 10. Without the presence of fruits, all of the empty lines except line 5 has the largest number of impacts at the last transfer points due to the sensor bouncing around the hopper. However, the fruits help reduce the bouncing which can be seen on line 1 and 2 whose number of impacts at the last transfer points are only 4.0 and 1.5. As a result, the total number of impacts on line 1 and 2 (less than 20) are also smaller than the empty lines. For other transfer points, the number of impacts varies from 1.0 to 12.3. Small number of impacts were found at the transfer points when the sensor was dropped on color sorter (1 to 2.6) and soft-fruit sorter (1.2 to 5.2). The reason may be due to the fast moving speed of the color and soft-fruit sorter conveyor belt that prevented bouncing of the sensor at this point.

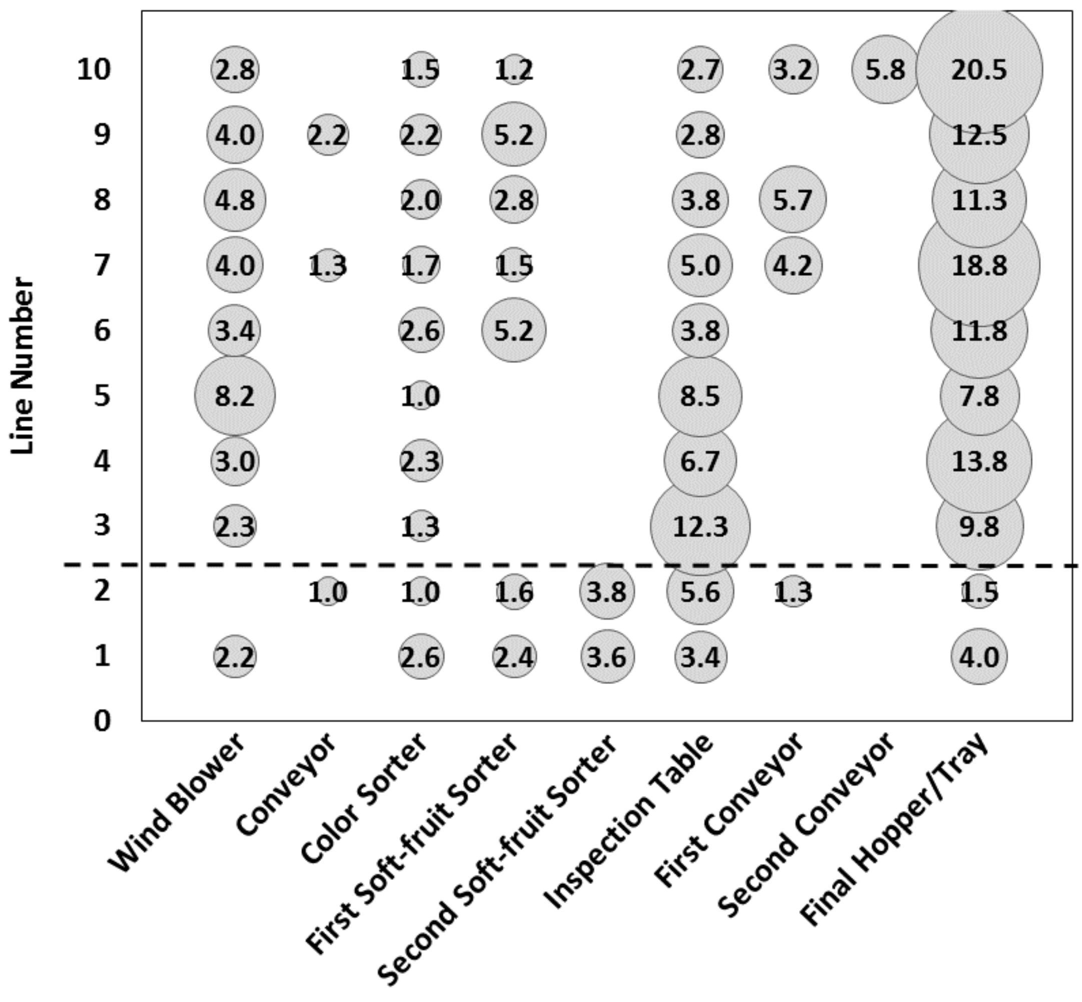


Figure 3.6. Bubble plot of the average number of impacts for the transfer point when transferred onto indicated component. The value is proportional to the area of the circle. The two packing line under the dash line were tested with blueberries.

Based on the impacts measured on different transfer points of different lines, an ideal line (Figure 3.7) is suggested. In the ideal line, there is only one lifting conveyor to transfer the fruit to blower, color and soft-fruit sorter. The color and soft-fruit sorter are installed on one conveyor belt so there is no drop between them. Using ramps at transfer points to reduce the speed of the fruit after coming from color and soft-fruit sorter. No additional conveyor between the inspection table and clamshell filler. Hard surfaces, for example, ramps, hopper of the clamshell filter and side wall of the conveyors, are padded to avoid direct impacts with fruits. The drop height of each transfer point were kept at the minimum feasible height.

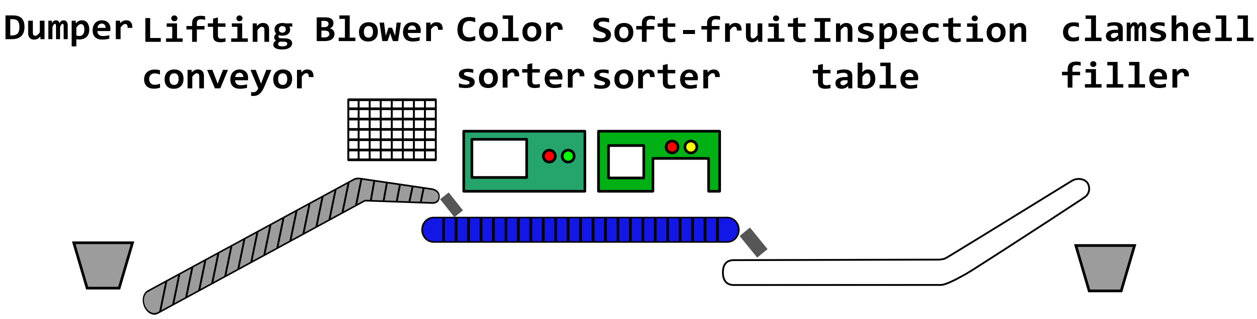


Figure 3.7. An ideal packing line schematic.

3.3.4 Impacts Level of Line 11

The BIRD II sensor recorded different average, maximum and cumulative peakG at the padded transfer points (Figure 3.8) between padded and unpadded line. T test showed that there is significant difference (p value$<$0.001) in the average, maximum and accumulated peakG at transfer point to the first and second conveyor between the unpadded and padded line. For the transfer point to inspection table, there is significant difference (p value$<$0.001) in average and maximum peakG, but not in cumulative peakG due to the large number of small impacts below 25 g in the unpadded line. No significant difference in average and maximum peakG is found at the last transfer point, but significant difference (p value = 0.0229) is found in accumulated peakG. The video shows that the sensor bounced several times within the hopper. Since only one side of the hopper being padded, the sensor could hit the unpadded side directly and record large impacts. Therefore, these bounces could be the reason for being no significant difference between the unpadded and padded line. The maximum peakG value of the transfer points to inspection table, the first and second conveyor are reduced by 59%, 47% and 54%, respectively. The padding avoids the direct contact of the sensor with the hard surface, and thus reduces the impact level. Therefore, cushioning the transfer points is an inexpensive and effective way to reduce the impact damage.

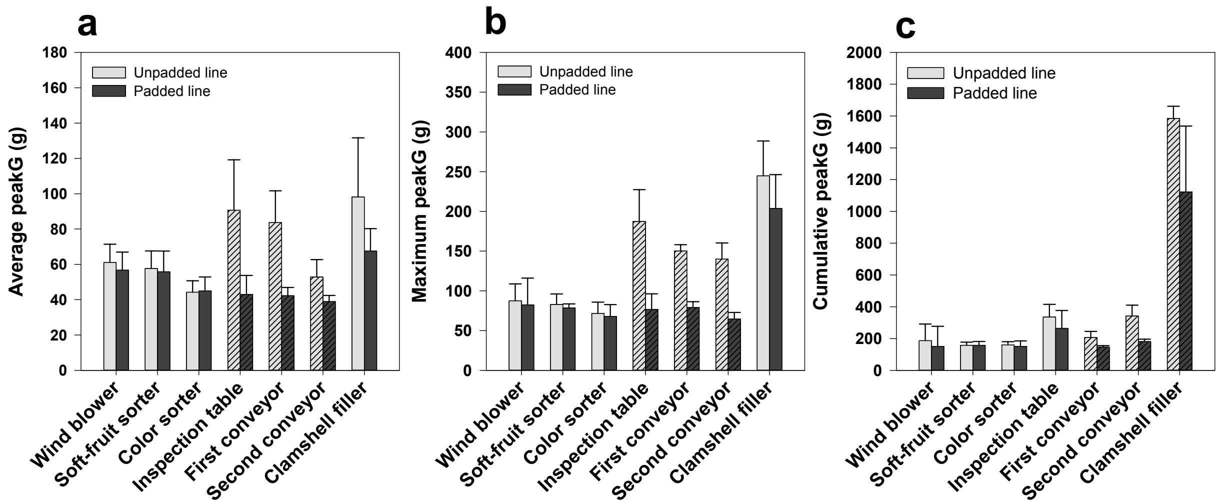


Figure 3.8. Average, maximum and cumulative peakG of each section when sensor was dropped on indicated line part on line 11. Significant difference (at significant level of 0.05) were found on the line part with pattern fill. g = 9.8 m/s^2.

3.3.5 Estimate the fruit bruising rate

Yu et al. developed an correlation model between the fruit bruising rate and the impact recorded by the BIRD I sensor based on the peakG and velocity change plot [30]. Using the model described in the paper, the bruising rate was estimated based on the impacts recorded on the 10 packing lines using BIRD I. The plot of peakG vs. velocity change of the impacts from all the replicates of the 10 lines was shown in Figure 3.8. The plot shows that most of the impacts are located in the "<26% Bruising area" which means these impact could create bruising rate less than 26%. Several impacts are outside the "<26% Bruising area" which could cause fruit bruising rate larger than 26%. Since different blueberry cultivar has different resistance to impacts, these estimation was only valid for the blueberry cultivar of ”Scintilla”. The correlation model only has one line to indicate different bruising rate, therefore, more detailed correlation model with multiple bruising rate lines us needed in order to more accurately estimate the bruising rate caused by the impacts. Additionally, since the model only considers the fruit bruising rate under one impact, the bruising damage caused by the packing line could be server than the bruising rate estimated by the model since the blueberry experienced multiple impacts during the packing line. However, this model gives a rough estimation of the fruit bruising created by the tested packing lines.

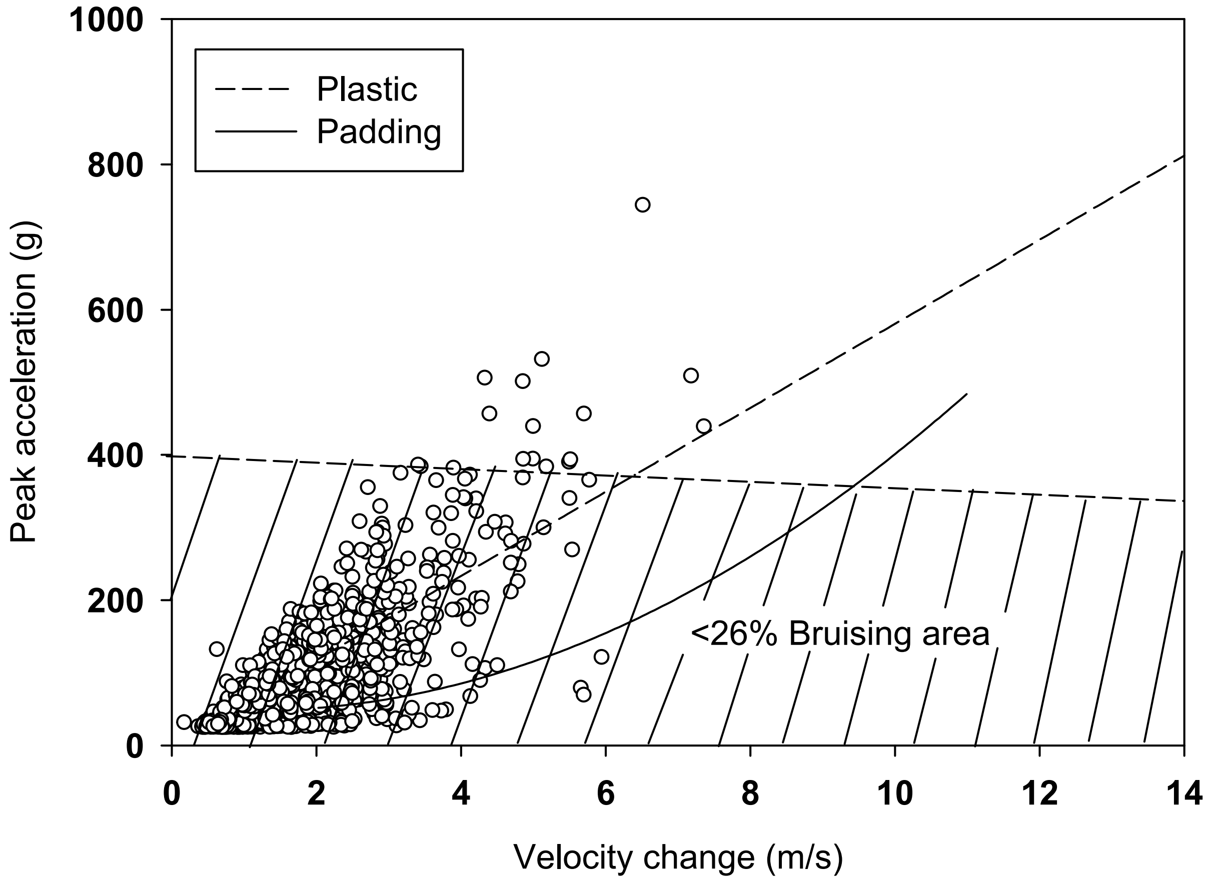


Figure 3.9. Plot of peakG vs. velocity change using all the impacts recorded in all the replicates of the 10 packing lines measured by BIRD I. The dotted and solid line shows the plot measured by BIRD I sensor on plastic and padding sheet respectively. The bruising rate was measured using blueberry cultivar of ”Scintilla”. g = 9.8 m/s^2.

3.4 Conclusion

This study quantitatively measured the mechanical impacts created during the packing line process using the BIRD sensor. Line 1 - 10 were tested using BIRD I sensor and line 11 was tested using BIRD II sensor. Line 11 was also modified by adding padding on critical transfer points. Major conclusions of this study are:

1. There were many transfer points that created high impact level and most of them have hard surfaces. The highest impact level was caused by clamshell filler.
2. The presence of fruits could lower the impact on some transfer points due to the cushioning from the fruit, and therefore, impact level may be overestimated for the packing lines tested without any fruit.
3. The smaller impact level recorded on line 11 after padding showed that the cushioning critical transfer points is an inexpensive and efficient way to reduce the impact damage.
4. For line 1 to 10, most of the impacts could cause a bruising rate less than 26% while several impact could cause bruising rate greater than 26%.

CHAPTER 4

CONCLUSION

This thesis described the development and application of the second generation Berry Impact Recording Device (BIRD II) with smaller size and lighter weight than BIRD I. The BIRD II sensor showed better precision and uniformity than BIRD I. Eleven commercial blueberry packing lines were tested using both BIRD I and BIRD II sensors. The results showed that most of the large impacts occurred at the transfer points and padding these transfer points can reduce the impacts efficiently.

4.1 Contribution

The development of the BIRD II sensor improved the design of the BIRD I sensor in four aspects: 1) the size and the weight was reduced significantly, making BIRD II better represent the behavior of the real blueberry in machine harvesters and packing lines; 2) the robustness and usability were enhanced by removing the interface box and replacing the serial communication with USB between the sensor and the PC directly. 3) The software programs for both the microcontroller and PC were redesigned to improve the performance and functionality; 4) the cost of the sensor was reduced significantly due to the low cost of the accelerometer and removal of the interface box ; 4) the performance of the sensor in terms of accuracy, precision and uniformity was improved. The sensor was designed primarily for small fruits and vegetables, however, it also can be applied to large fruits and vegetables by modifying the housing design of the sensor. In spite of the original goal of using it for agricultural products, the sensor can also be used in other fields, for example, geology, sports science, and virtual reality.

The results of the evaluation of the blueberry packing lines revealed the impact damage to blueberries quantitatively during the packing process, which was never done before. These quantitative measurements provided useful information and guidance for the manufacturers of blueberry packing/sorting equipment and packers when designing and installing the packing lines.

4.2 Future Work

The BIRD II sensor was proven to be a useful tool for evaluating the mechanical damage to small fruits and vegetables. Potential improvement and application of the sensor could be carried out from the following aspects:

- Current design of the sensor needs a wire cable to communicate with the PC and charge the sensor, thus the sensor can not be made water proof since the connector is exposed to the air. Possible solutions are to use wireless communication and wireless charging to make the sensor communicate with the PC and be charged without using a wire cable.
- Mobile app to configure the sensor and download data could be developed to further assist the usage of the sensor in the field.
- More detailed relationship between the impact data recorded by the sensor and blueberry bruising rate should be established in the laboratory so that the real bruising rate caused by the packing line can be more accurately estimated based on the impact data.
- The sensor can be used for large fruits and vegetables. For example, the sensor can be embedded into a potato or apple. In this case, the sensor can record the real response when the fruits and vegetables interact with the mechanical parts.

REFERENCES

[1] USDA, "Crop values 2013 summary (february 2014)," tech. rep., United States Department of Agriculture, 2014.

[2] USDA, "Noncitrus fruits and nuts 2013 summary," tech. rep., United States Department of Agriculture, 2014.

[3] D. Martinez-Romero, M. Serrano, A. Carbonell, S. Castillo, F. Riquelme, and D. Valero, "Mechanical damage during fruit post-harvest handling: technical and physiological implications," in *Production practices and quality assessment of food crops*, pp. 233–252, Springer, 2004.

[4] A. Bollen, I. Woodhead, and B. D. Rue, "Compression forces and damage in the postharvest handling system," *ASAE, Guanajuato, Mexico*, pp. 168–175, 1995.

[5] G. Brown *et al.*, "Harvest mechanization status for horticultural crops.," *ASAE Paper*, no. 80-1532, 1980.

[6] C. Safley, W. Cline, and C. Mainland, "Estimated costs of producing, harvesting, and marketing blueberries in the southeastern united states."

[7] G. Brown, N. Schulte, E. Timm, R. Beaudry, D. Peterson, J. Hancock, and F. Takeda, "Estimates of mechanization effects on fresh blueberry quality," *Applied engineering in agriculture (USA)*, 1996.

[8] J. N. Moore, "The blueberry industry of north america," *HortTechnology*, vol. 4, no. 2, pp. 96–102, 1994.

[9] G. Brown, N. Schulte Pason, E. Timm, C. Burton, D. Marshall, *et al.*, "Apple packing line impact damage reduction.," *Applied Engineering in Agriculture*, vol. 6, no. 6, pp. 759–764, 1990.

[10] C. Morrow and T. Ruscitti, "Using an instrumented sphere on potato packing lines.," *Paper-American Society of Agricultural Engineers*, no. 90-6028, 1990.

[11] S. Sargent, J. Brecht, J. Zoellner, *et al.*, "Analyses of tomato and bell pepper packing lines using the instrumented sphere.," *Paper-American Society of Agricultural Engineers*, 1990.

[12] G. Brown, N. Schulte Pason, E. Timm, *et al.*, "Impact classification using the instrumented sphere.," *Paper-American Society of Agricultural Engineers*, no. 90-6001, 1990.

[13] I. Techmark, "Ird kit contents," 2013.

[14] P. Yu, C. Li, F. Takeda, G. Krewer, G. Rains, and T. Hamrita, "Quantitative evaluation of a rotary blueberry mechanical harvester using a miniature instrumented sphere," *Computers and Electronics in Agriculture*, vol. 88, pp. 25–31, 2012.

[15] P. Yu, C. Li, F. Takeda, G. Krewer, G. Rains, and T. Hamrita, "Measurement of mechanical impacts created by rotary, slapper, and sway blueberry mechanical harvesters," *Computers and Electronics in Agriculture*, vol. 101, pp. 84–92, 2014.

[16] B. Herold, I. Truppel, G. Siering, and M. Geyer, "A pressure measuring sphere for monitoring handling of fruit and vegetables," *Computers and electronics in agriculture*, vol. 15, no. 1, pp. 73–88, 1996.

[17] R. C. Rider, R. Fridley, and M. OBRIEN, “Elastic behavior of a pseudo-fruit for determining bruise damage to fruit during mechanized handling,” *Transactions of the ASAE*, vol. 16, no. 2, pp. 241–244, 1973.

[18] B. Tennes, H. Zapp, G. Brown, and S. Ehlert, “Self-contained impact detection device: Calibration and accuracy,” 1988.

[19] H. Zapp, S. Ehlert, G. Brown, P. Armstrong, S. Sober, *et al.*, “Advanced instrumented sphere (is) for impact measurements.,” *Transactions of the ASAE*, vol. 33, no. 3, pp. 955–960, 1990.

[20] M. L. Avery, K. J. Goocher, and M. A. Cone, “Handling efficiency and berry size preferences of cedar waxwings,” *The Wilson Bulletin*, pp. 604–611, 1993.

[21] P. Yu, C. Li, G. Rains, and T. Hamrita, “Development of the berry impact recording device sensing system: Hardware design and calibration,” *Computers and Electronics in Agriculture*, vol. 79, no. 2, pp. 103–111, 2011.

[22] P. Yu, C. Li, G. Rains, and T. Hamrita, “Development of the berry impact recording device sensing system: software,” *Computers and Electronics in Agriculture*, vol. 77, no. 2, pp. 195–203, 2011.

[23] R. Saftner, J. Polashock, M. Ehlenfeldt, and B. Vinyard, “Instrumental and sensory quality characteristics of blueberry fruit from twelve cultivars,” *Postharvest biology and technology*, vol. 49, no. 1, pp. 19–26, 2008.

[24] T. V. Canneyt, E. Tijskens, H. Ramon, R. Verschoore, and B. Sonck, “Characterisation of a potato-shaped instrumented device,” *Biosystems engineering*, vol. 86, no. 3, pp. 275–285, 2003.

[25] USDA, “Noncitrus fruits and nuts (2012 preliminary summary),” tech. rep., United States Department of Agriculture, 2013.

[26] R. Mathew and G. Hyde, “Potato impact damage thresholds,” *Transactions of the ASAE*, vol. 40, no. 3, pp. 705–709, 1997.

[27] S. Sober, H. Zapp, and G. Brown, “Simulated packing line impacts for apple bruise prediction,” *Transactions of the ASAE (USA)*, 1990.

[28] E. Timm, G. Brown, R. Brook, N. Schulte, and C. Burton, “Impact bruise estimates for onion packing lines,” *Applied engineering in agriculture (USA)*, 1991.

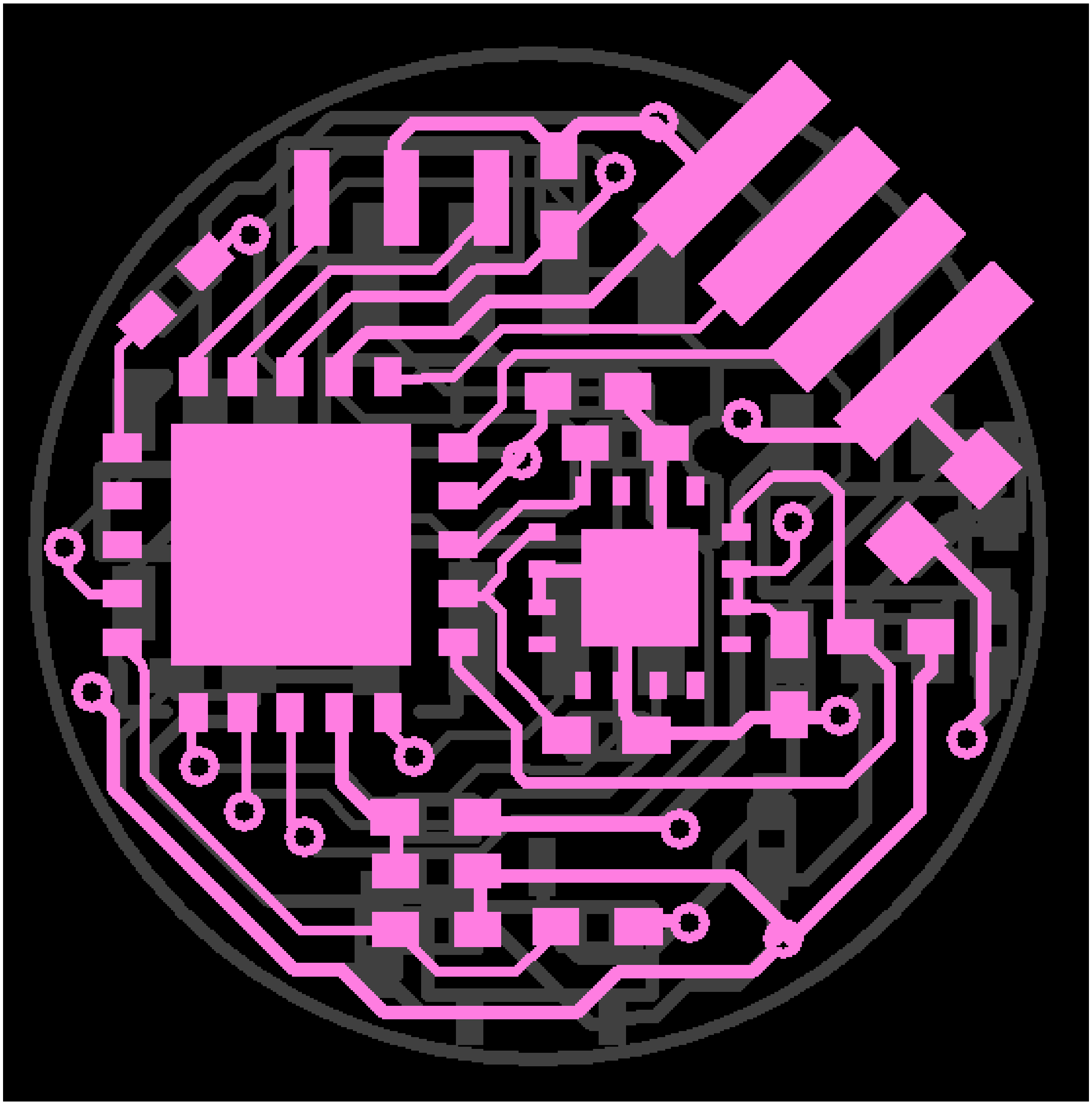
[29] F. Garcıa-Ramos, J. Ortiz-Cañavate, and M. Ruiz-Altisent, “Decelerator elements for ramp transfer points in fruit packing lines,” *Journal of food engineering*, vol. 59, no. 4, pp. 331–337, 2003.

[30] P. Yu, C. Li, F. Takeda, and G. Krewer, “Visual bruise assessment and analysis of mechanical impact measurement in southern highbush blueberries,” *Applied Engineering in Agriculture*, vol. 30, no. 1, pp. 29–37, 2014.

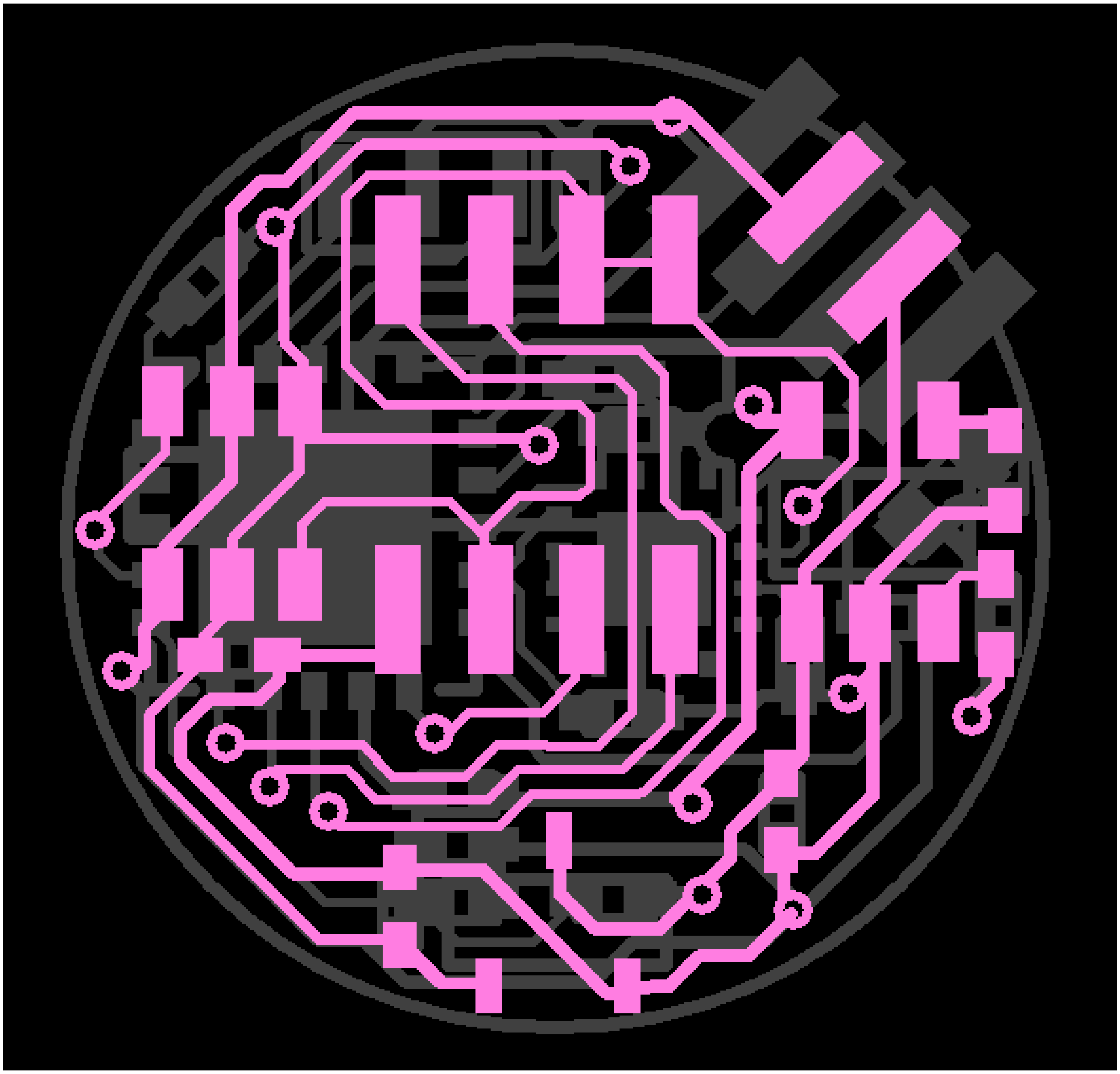
APPENDIX

Appendix A Sensor PCB Layout

Top Side

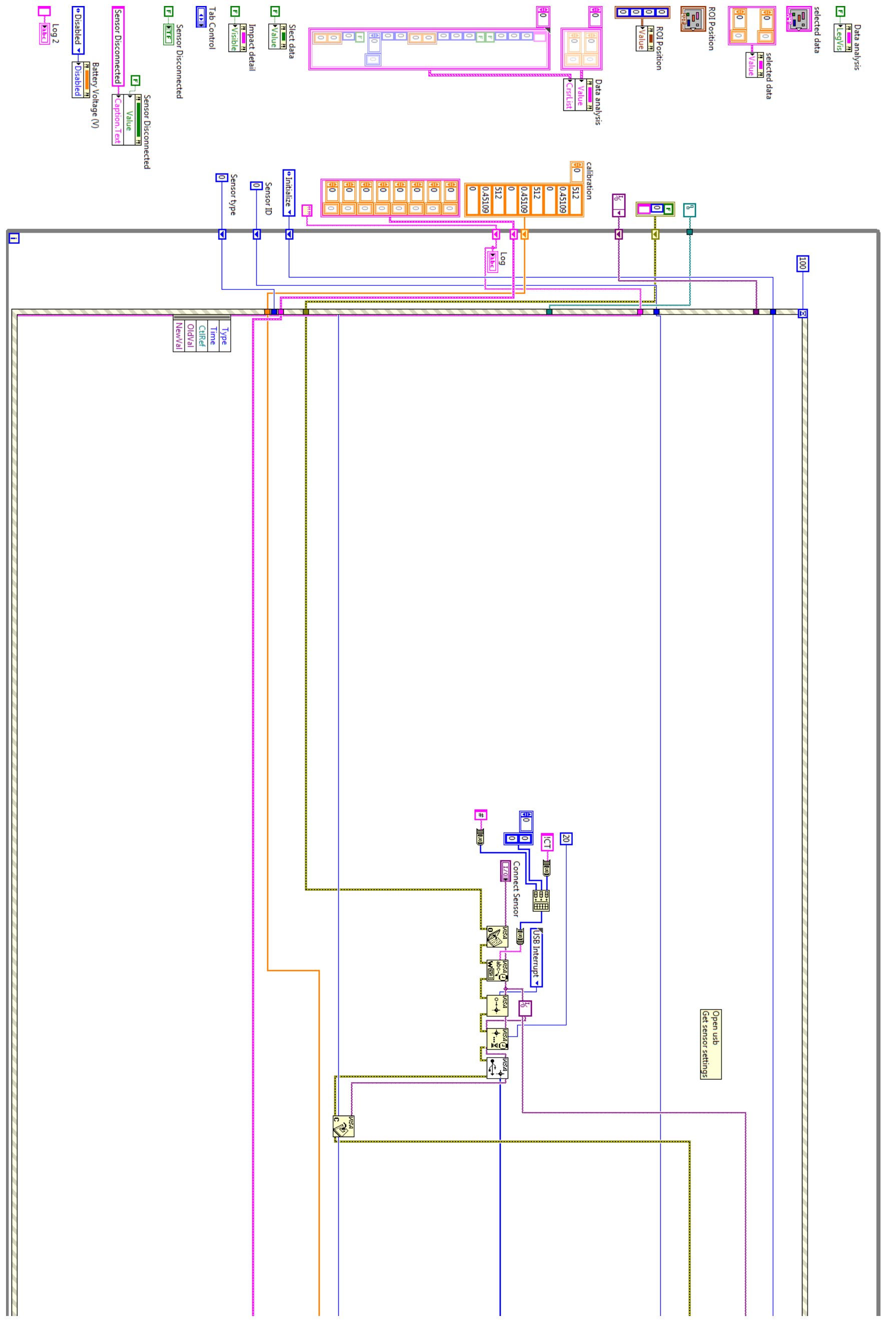


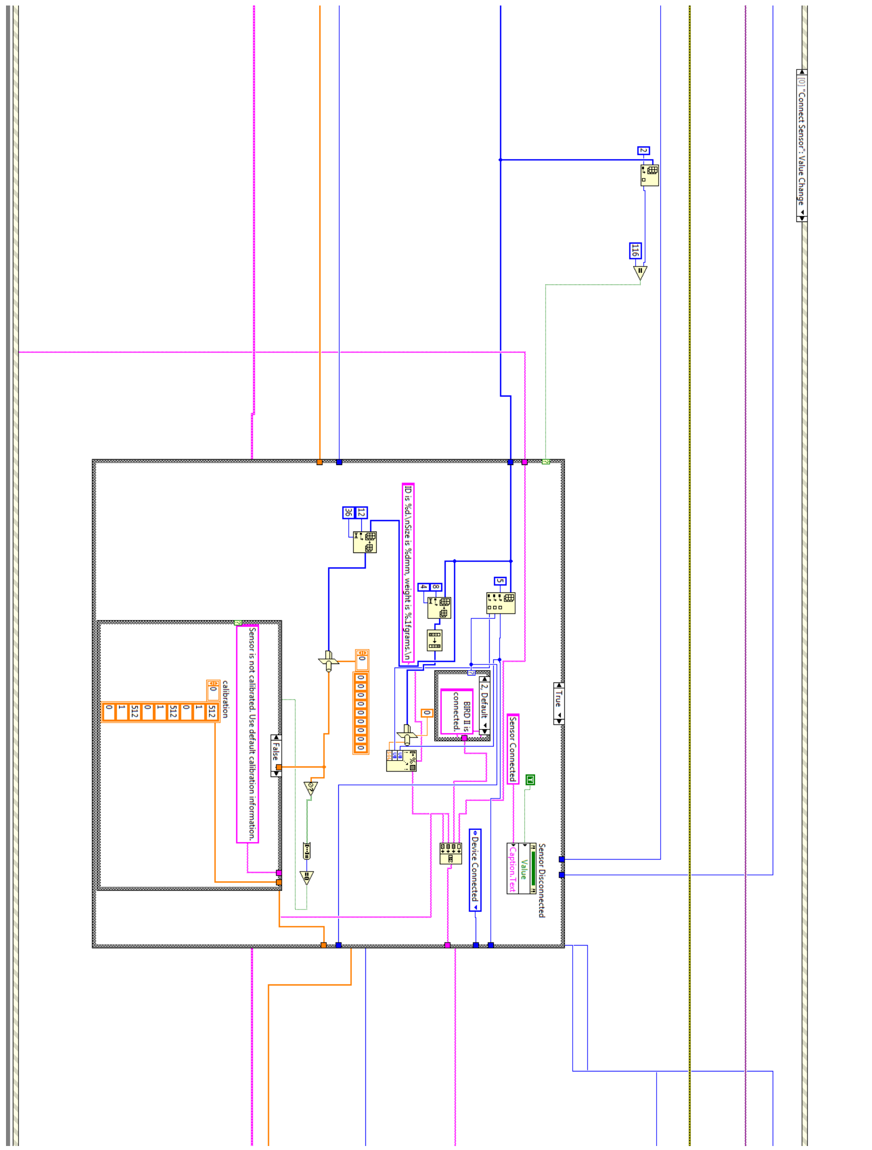
Bottom Side

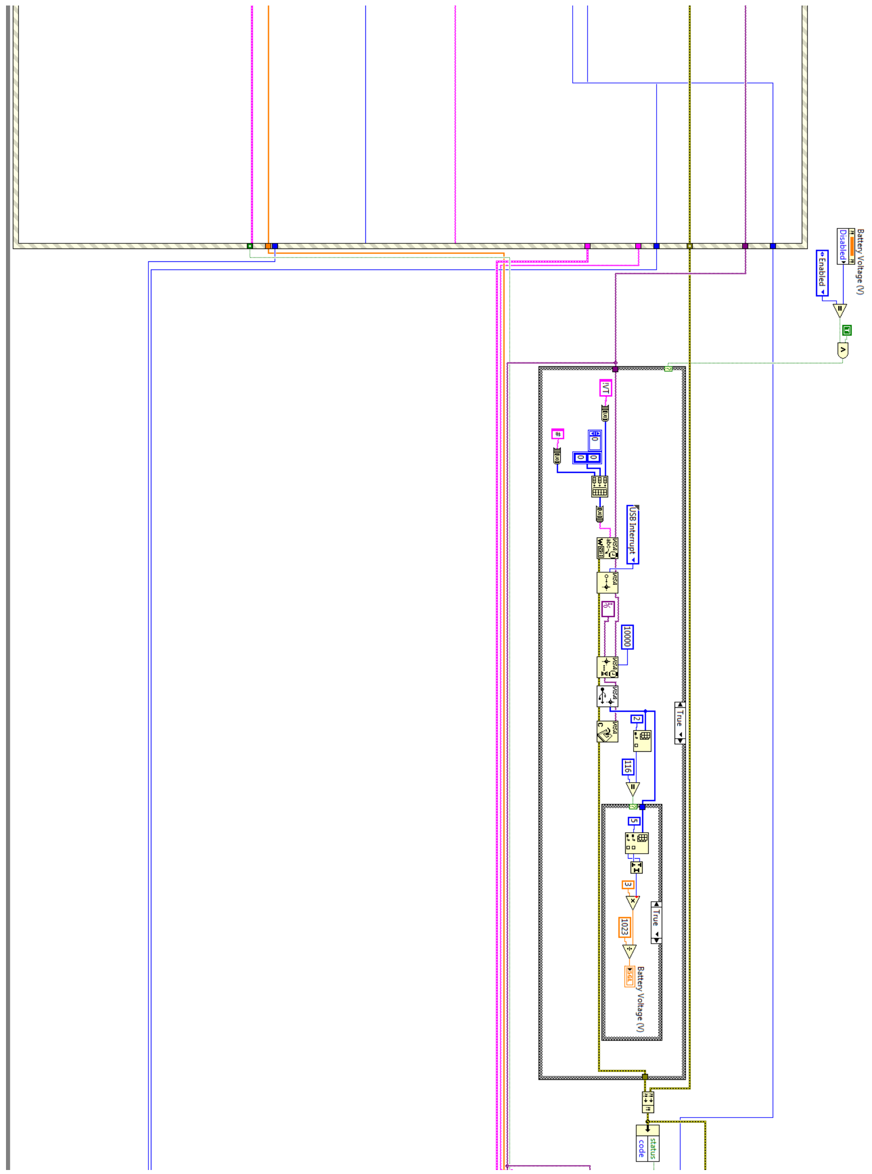


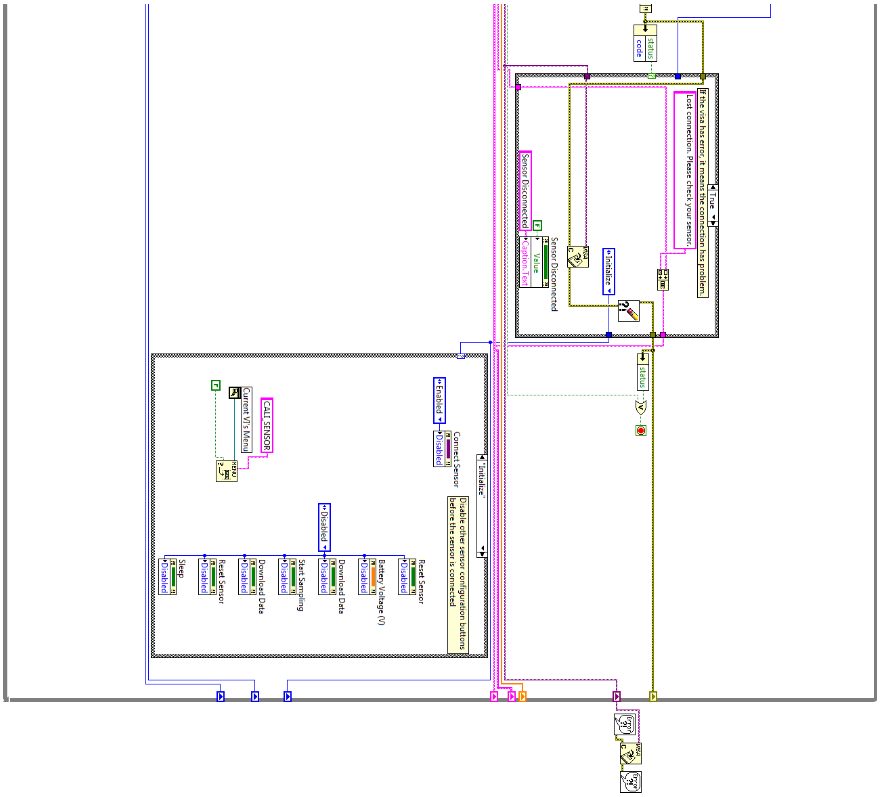
Appendix B Partial Source Code of pBIRD

Main VI

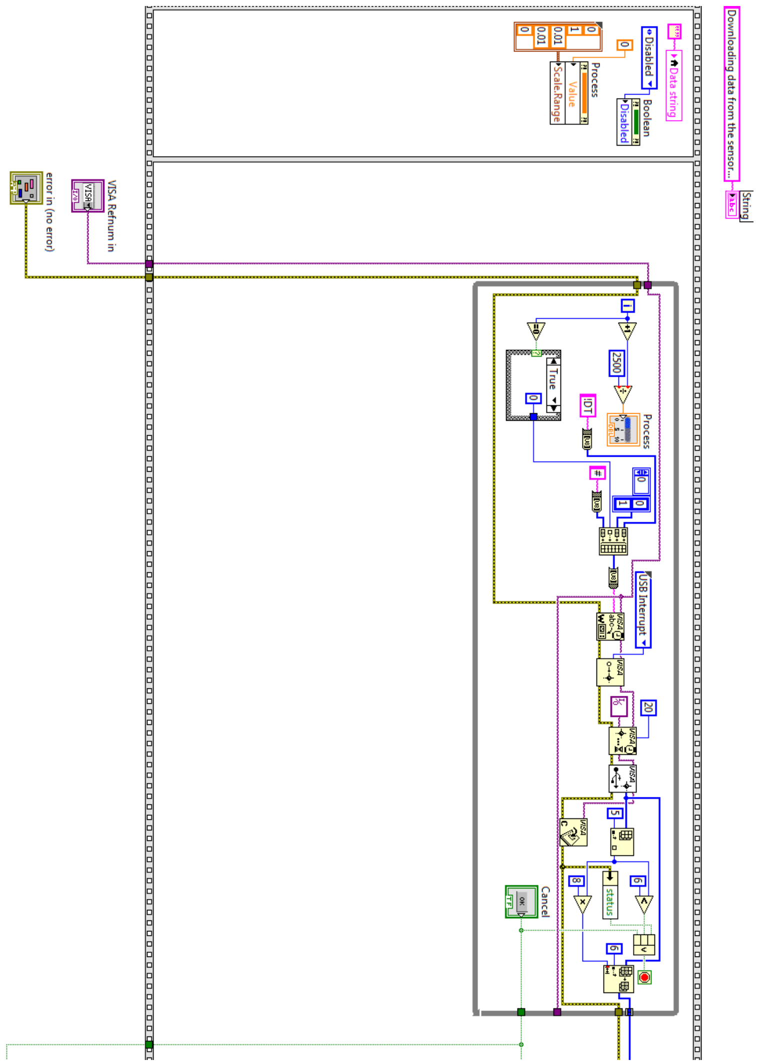


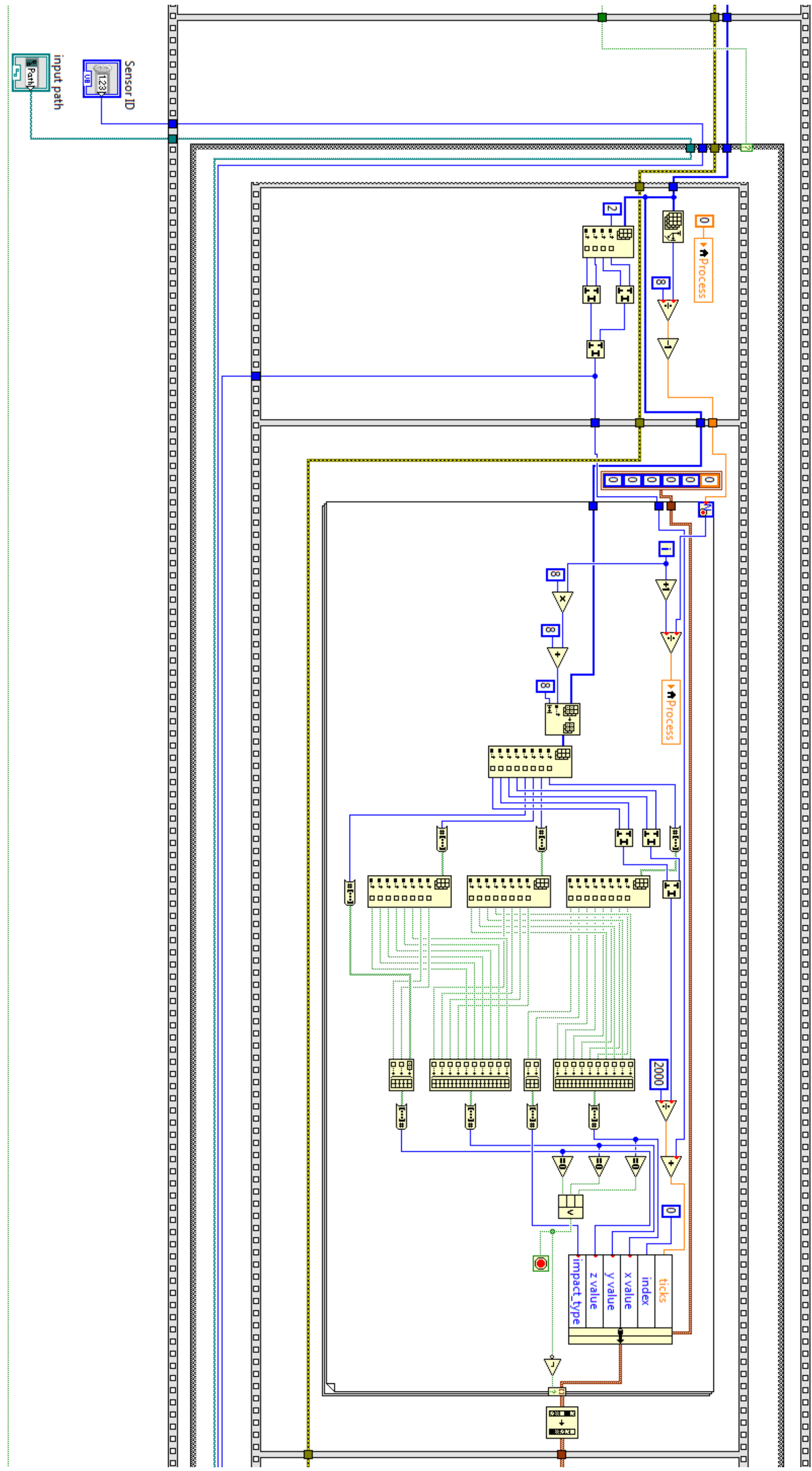

Sensor is not calibrated. Use default calibration information.
calibration
BIRD II is connected.
Sensor Connected
Device Connected
Sensor Disconnected
True
False

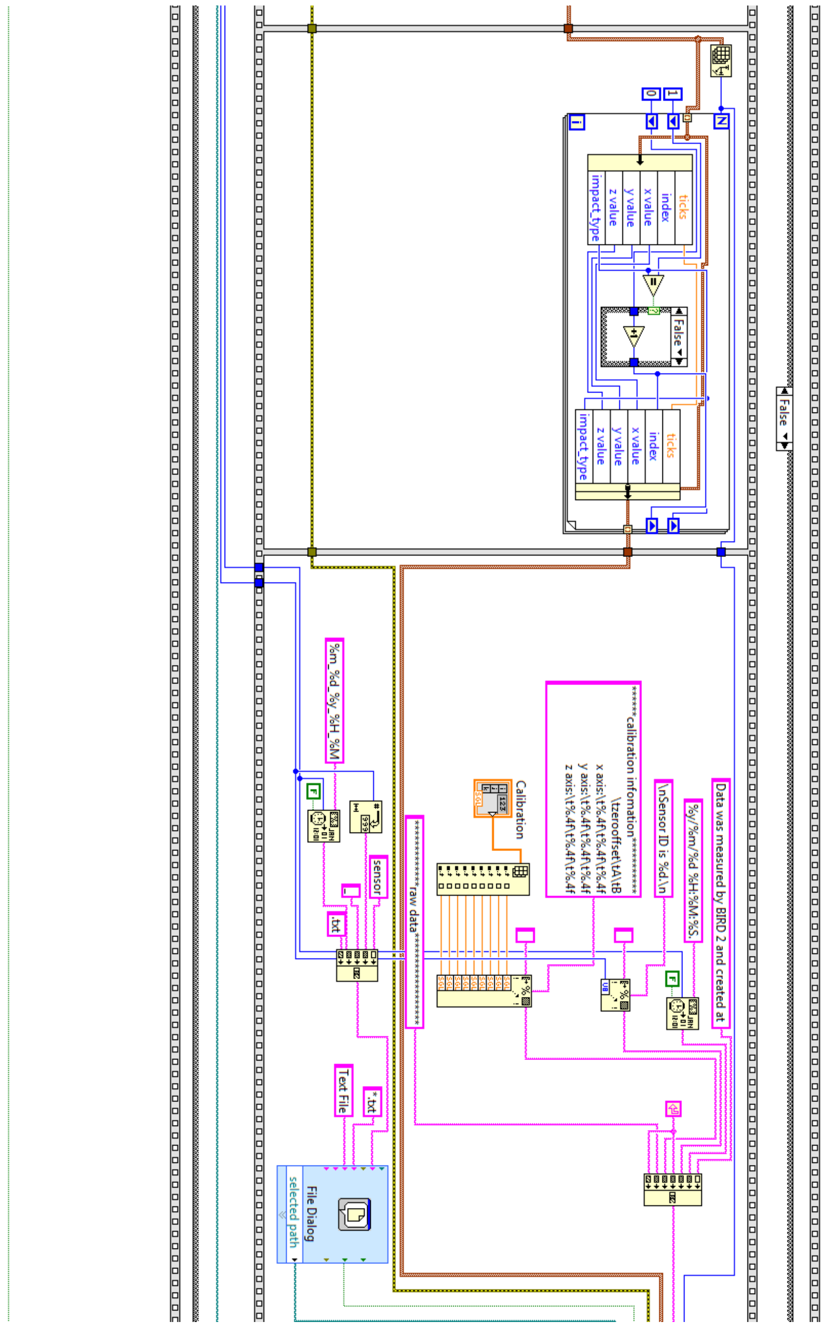

Battery Voltage (V)
Enabled
Disabled
USB Interrupt
10000
True
116
1023
True
Battery Voltage (V)
status
code

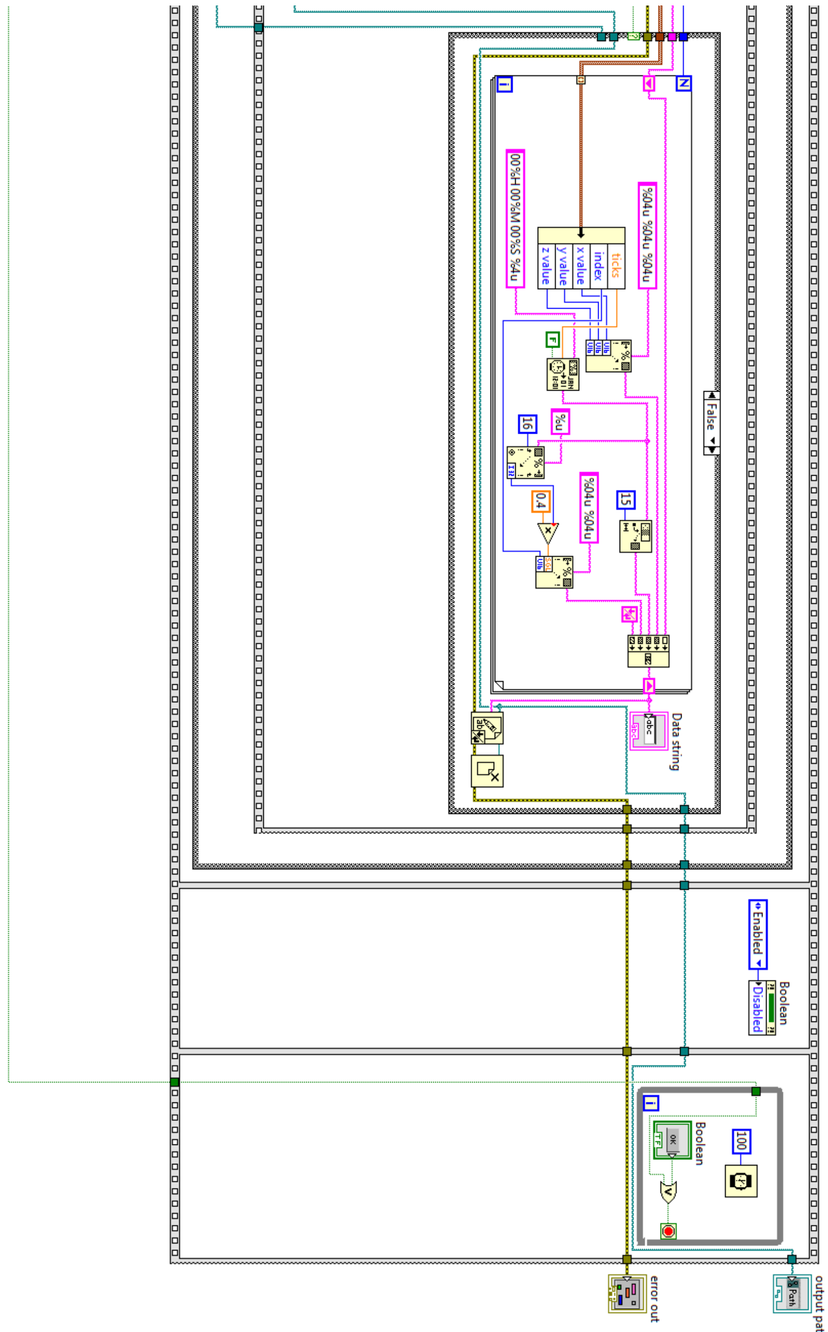

If the visa has error, it means the connection has problem.
Lost connection. Please check your sensor.
Sensor Disconnected
Initialize
Disable other sensor configuration buttons before the sensor is connected
Connect Sensor
CALL SENSOR
Current VI's Menu
Reset Sensor
Battery Voltage (V)
Download Data
Start Sampling
Sleep

Data download

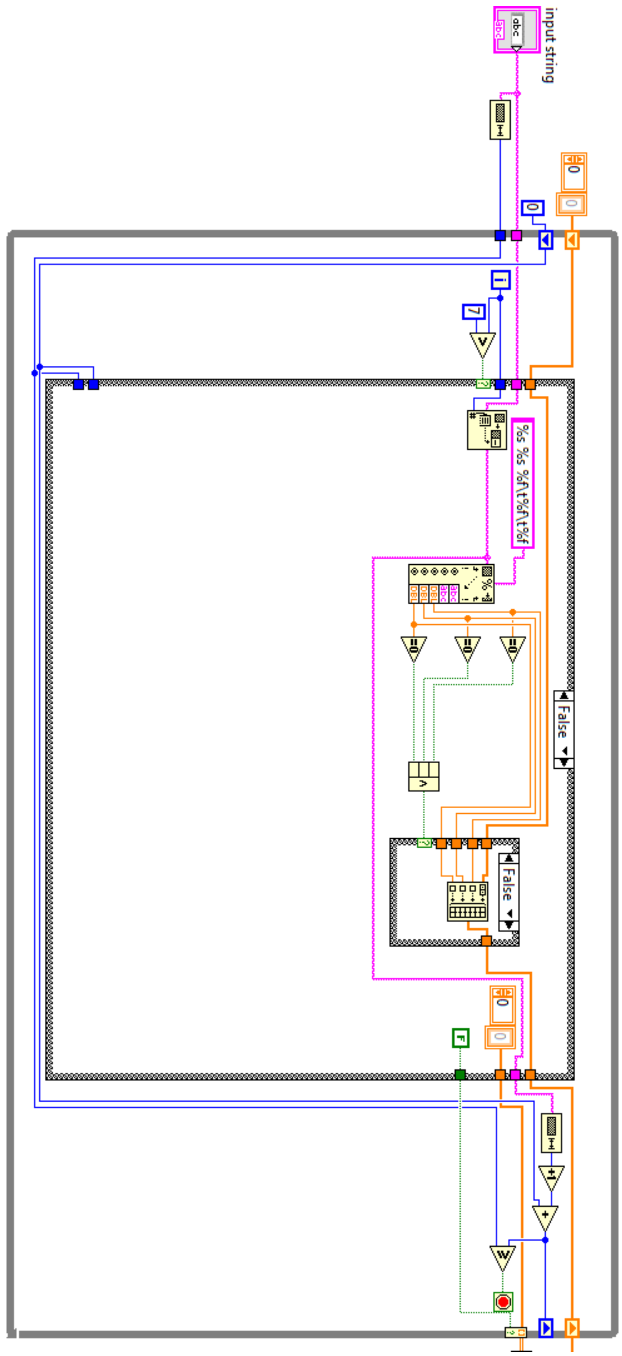


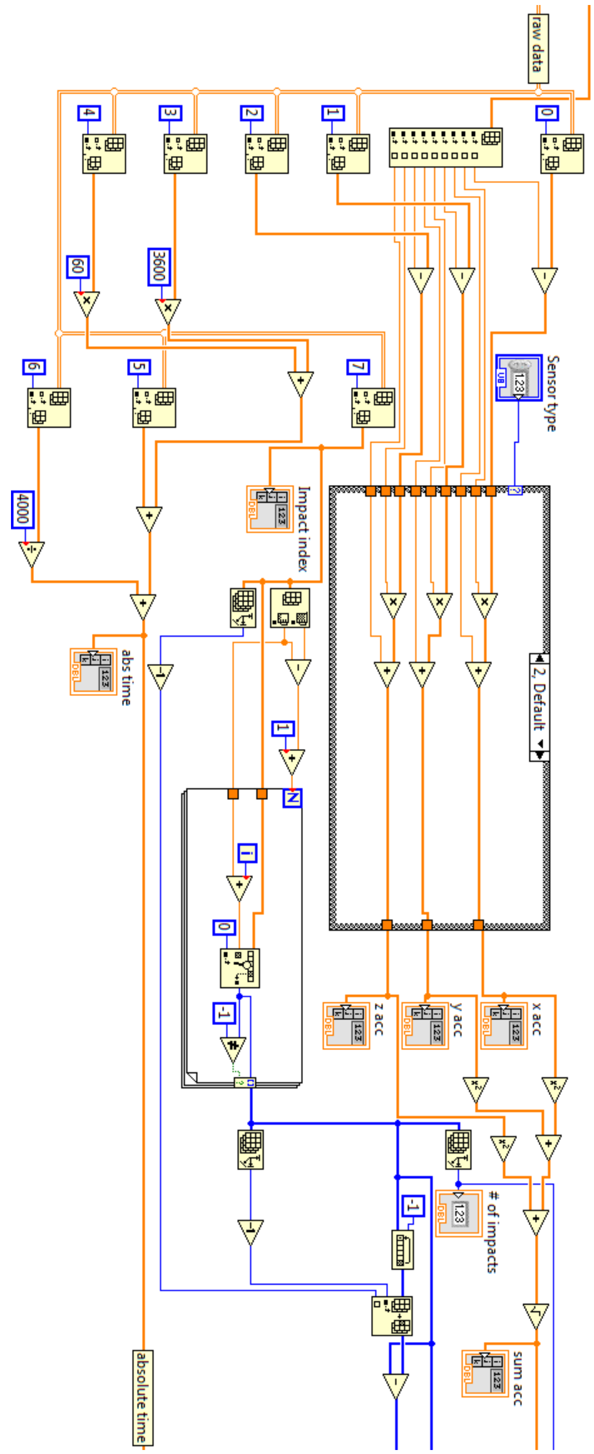

input path
Sensor ID
Process
Process
ticks
index
x value
y value
z value
impact_type
2000

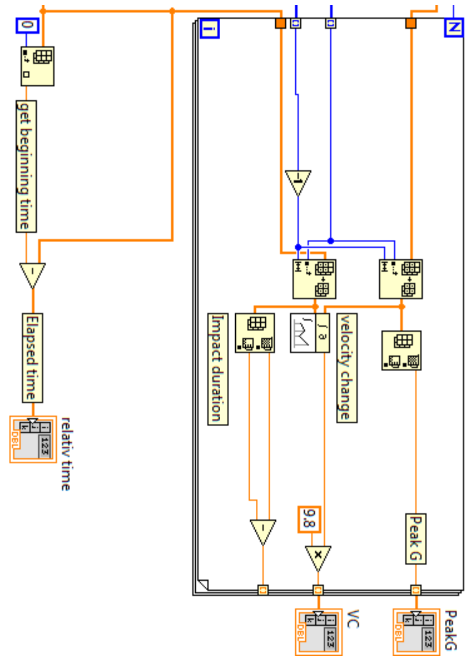

ticks
index
x value
y value
z value
impact_type
False
Calibration
%m_%d_%y_%H_%M
sensor
.txt
raw data
calibration information
\nSensor ID is %d.\n
%y/%m/%d %H:%M:%S
Data was measured by BIRD 2 and created at
Text File
*.txt
File Dialog
selected path


00%H 00%M 00%S %4u
ticks
index
x value
y value
z value
%04u %04u %04u
False
16
%u
0.4
%04u %04u
15
Data string
Enabled
Boolean
Disabled
100
Boolean
error out
output path

Data processing




raw data
Sensor type
Impact index
abs time
2, Default
z acc
y acc
x acc
# of impacts
sum acc
absolute time


get beginning time
Elapsed time
relativ time
Impact duration
velocity change
9.8
Peak G
VC
PeakG