Automatic Harvesting for Sweet Peppers in Greenhouse Horticulture

Shivaji Gunga BACHCHE

A dissertation submitted in partial fulfillment of the requirements
for the degree of
Doctor of Philosophy in
Intelligent Mechanical Systems Engineering

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ABSTRACT

The rapid growth in the world population demands a constant food supply with quality. In Asia, decreasing farmer and labor population due to various factors is a serious problem that leads to increase in labor cost, higher input harvesting energy consumption and less resource utilization, especially in Japan. As a result, to solve this problem, researchers are engaged to provide long term and low tech solutions in terms of mechanization and automation of agriculture sector by using highly sophisticated robots that replace manpower in tasks when a person performs worse than an automatic device in terms of precision, consistency and working cycle. The agricultural production rates are significantly influenced by utilization of robots and tools and techniques developed for decision support system. To obtain the automatic system in agriculture sector, three main problems need to be solved: (1) the guidance of the robot through the crops, (2) the location and characterization of the fruit on the trees and (3) the grasping and detachment of each piece.

In Japan, green sweet pepper is the 5th most important fruit vegetable grown on approximately 3430 hector area of land producing 142,000 tons yield which needs not only high man power but also high input energy consumption during harvesting operation leading to increase in labor cost and production cost. This issue also connects to decreasing population of Japan in recent decades. On the other hand, detection of fruits in natural background is difficult when color of fruits and background, such as the leaves and stems or fruits, are similarly greenish. As both, green sweet pepper and leaves has almost same color and due to that it is very difficult to recognize them separately during automatic harvesting. Thus, by considering these issues, a green sweet pepper was selected for the research study. This research focuses on location and characterization of green sweet peppers on trees and grasping and detachment of sweet peppers during harvesting operation in the greenhouse horticulture.

By considering a need of simple and economical robot end-effector, several types of prototypes were designed and developed based on various mechanisms, parameters and materials; and tested for their performances. The prototype model were first modeled and simulated in the software to observe the static and fatigue characteristics of each component in the system and obtain the optimal design parameters for prototyping

environment. After the successful and satisfactory results obtained from the simulation; the prototypes were built and verified for performance and reliability. A prototype based on mechanical contact gripping strategy showed significant results during harvesting operation under several situations. This picking system prototype showed significant results under selected testing conditions with 97.91% performance efficiency, 1.1s to perform the harvesting operation and no physical damage was observed to the harvested fruits. Considering the fruit shelf life and quality measures, thermal cutting system prototypes were developed based on amplified voltage and current potentials. In electric arc thermal cutting system, 1mm and 2mm diameter electrodes were tested for harvesting operation in which 1mm diameter electrodes found significant for cutting fruit stem of 5mm diameter in 2.2s. In temperature arc thermal cutting system, 0.02mm, 0.5mm and 1mm diameter nichrome wires were tested for harvesting operation in which 0.5mm and 1mm diameter nichrome wires found significantly effective for cutting fruit stem of 5mm diameter in 1.5s and 1.4s respectively. Among the two prototypes, temperature arc thermal cutting system demonstrated good results in which based on physical configuration of prototype, 0.5mm diameter nichrome wire was recommended for harvesting operation. By adopting thermal cutting system, the physical damage to fruits could be avoided and there was no viral or fungal transformation occurred within the harvested fruits which considerably help to preserve the quality and shelf life of fruits up to 15 days at normal room conditions.

A color recognition system and fruit detection algorithm was developed and tested for several color space models based on color making attributes and reflection feature attributes to find out the significant color space model for detection of green sweet peppers in natural background. In case of color images, HSV color space model was found more significant with high percentage of green sweet pepper detection followed by HSI; as both provides information in terms of hue/lightness/chroma or hue/lightness/saturation which are often more relevant to discriminate the fruit from image at specific thresholding value. In HSV color space model, based on image histogram analysis, it was found that there was significant difference between reflection from fruits an reflection from leaves and stems. Due to this higher reflection feature attribute, the fruit visibility was higher in HSV color space model followed by HSI color space model when compared with other color space models in which the fruit visibility was low due to inconsistent or lack of reflection feature attributes. The recognition rate found higher for HSV color space model as 84% while for HSI as 72% which was further categorized into 4 different groups based on various conditions that occurs during harvesting process. Location and orientation i.e. 3D coordinates and inclination angle of detected fruit stem with respect to vertical axis were obtained. This positional information of detected green sweet peppers was found highly reliable in which the depth accuracy errors and disparity parallax errors were minimum when distance between cameras and fruit was 500 to 600 mm and distance between two cameras maintained to 100 mm.

A multispectral IR recognition system and fruit detection algorithm was developed and tested during day and night time under several selected conditions in which IR 96 optical filter found significant to detect the sweet peppers in day time without any artificial IR lighting. IR 78 and IR 80 optical filters were found not significant to locate the fruits as these filters were highly sensible to artificial IR lighting intensity and it was also found that there was no color difference observed between fruits and background. IR 90 optical filter was found moderately suitable with reasonable fruit visibility percentage for detection of fruits in night time at high light intensities but the results were unstable as the change in image capture camera angle and distance to fruits were found as influencing factors for successful detection of sweet peppers. The histogram values of reflection feature attribute thresholding and light intensity thresholding had significant difference which made sweet pepper detection possible in night time based on reflection feature attribute. There was considerable difference found between color of fruits and rest of background which caused a partial detection of fruits with IR 90 in day time. IR 96 optical filter was found highly significant for fruit detection or multi-detection with high percentage of fruit visibility under several conditions during day time. There was significant color difference observed between fruits and rest of background which caused successful fruit detection and high fruit visibility percentage for single fruits, fruits with leaves or overlapped and occluded fruits by using low pass filter thresholding.

The fruit maturity determination algorithm was developed by using PCA analysis based on strong correlation of chlorophyll reflectance of fruits detected by IR 96 optical filter to IR wavelength. The single fruits or fruits with leaves whose detection was possible successfully, the maturity determination percentage was found higher compared with occluded and overlapped fruits. The maturity determination by using developed algorithm

was found high in G1 group (76.07%) and G2 group (58.90%) followed by decreasing trend for G3 and G4 groups. Unstable results were found when leaves or stems overlapped or occlude with the fruits and detected in recognition results as a part of detected fruits. This was due to the influence of chlorophyll reflectance from leaves and stems on chlorophyll reflectance of fruits in the recognized results of sweet peppers.

Keywords: Sweet pepper, gripper, simulation and modeling, thermal cutting, electric arc, temperature arc, recognition system, multispectral imaging, image processing, thresholding, maturity determination, automatic harvesting

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LIST OF ABBREVIATIONS

et al.	:	and others
viz.	:	videlicet
dof	:	degree of freedom
3D	:	3 Dimensional
S – N	:	Stress – Number of cycles
USB	:	Universal Serial Bus
I/O	:	Input / Output
PWM	:	Pulse Width Modulation
M	:	Module
T	:	Number of teeth
PA	:	Pressure Angle
FW	:	Face Width
NSD	:	Nominal Shaft Diameter
AC	:	Alternating Current
DC	:	Direct Current
EATCS	:	Electric Arc Thermal Cutting System
TATCS	:	Temperature Arc Thermal Cutting System
TK	:	Thermal Knife
CCD	:	Charge Coupled Device
LED	:	Light Emitting Diode
TV line	:	Transverse Vertical line
RGB	:	Red Green Blue
HSI	:	Hue Saturation Intensity
HSV	:	Hue Saturation Value
IR	:	Infrared
NIR	:	Near Infrared
PCA	:	Principle Component Analysis
N	:	Newton
N-m	:	Newton-meter
W	:	Watt
A	:	Ampere
V	:	Volt
kHz	:	Kilo Hertz
ha	:	hectare
t	:	tons
s	:	second / seconds
mm	:	millimeter
^0C	:	Degree Centigrade
nm	:	Nano meter
m	:	Meter
mA	:	mill amperes
Hz	:	Hertz
ϕ	:	Diameter
ρ	:	Rho
Ω	:	Ohm
%	:	Percentage

Chapter I

INTRODUCTION

1. INTRODUCTION

The drastic changes in automatization from computer numerically controlled machines that work in limited environmental factors to humanoid, space, surgical robots with artificial intelligence has been took place in last few decades. This chapter gives an insight into the developments and achievements in the agricultural robotics in past few decades; the background, problems, objectives, scope and limitations of the research study presented in this dissertation.

1.1 Background

Agriculture and food are the backbone of many developed and under developing countries that helps country to grow up their economical, social and individual status. The development of agriculture in traditional hunter-gatherer societies started around 10,000 years ago and has been crucial to the formation of human civilizations across the globe. Over the centuries agriculture has morphed into the modern large-scale bio-industry it is today, producing goods through the growing of plants, animals and other organisms in close interaction with the environment. The major changes in agriculture has occurred through domestication of crops and animals, weed control techniques, water management, fertilizer/pesticide application, genetic engineering and the large scale mechanization that ensued in the middle of 1990's. These major changes helped agriculture sector to grow up rapidly with mechanization and precision technologies by discovering incredible innovations and bringing various revolutions around the world.

In recent decades, advanced technology and latest results of scientific research have been largely applied in agriculture in order to improve the quality of products and to increase the productivity. The rapid growth in the world population demands a constant food supply with quality. In Asia, decreasing farmer and agricultural labor population due to various factors is a serious problem, especially in Japan [1.1]. As a result, to solve this problem, researchers are engaged to provide long term and low tech solutions in terms of mechanization and automation of agriculture sector by using highly sophisticated robots that can replace manpower in tasks when a person performs worse than an automatic device in terms of precision, consistency and working cycle.

1.2 Present Status of Fruit Harvesting Robotics

The development of robot system that enables harvesting autonomously has received considerable attention in the last decades but has gained least amount of technological development for satisfactory automation. In agriculture automation, the production systems should provide higher quality products at lower cost in order to become competitive when the agricultural production rates are significantly influenced by utilization of agricultural robots and tools and techniques developed for decision support system [1.2].

Among the various farm management operations, harvesting is an important operation which needs not only labor power but also high energy input with high resources. Most of the other farm management operations can be carried out by highly precise and accurate commercialized mechanization techniques but harvesting operation still has not gained the similar commercialization status which engaged many researchers to study and develop the agricultural robot applications for harvesting purpose. The study of agricultural robot applications for plant production presumably started with mechanical citrus harvesting system in 1968 [1.3]. Thereafter several achievements in fruit and vegetable handling have been found around the globe which helped to enhance the harvesting operation status in field management. Since 1968, the major achievements gained in the application of robotics for fruit harvesting are listed below in Table 1.1.

So far, no harvesting robot has reached the stage of commercialization, because of their low operation speeds, low fruit recognition rate in variable field conditions, low successful fruit harvesting rates, complexities in the robot manipulator movement control and high costs. To overcome these hurdles and provide a sophisticated robot technology that can replace human by means of various tasks and in order to achieve the commercialization status of fruit harvesting robots; many researchers are working on autonomous harvesting robots. The real time cost effective and fully automatic robotic fruit harvester might have a long way from the final commercial prototype yet, however, some interests for future research to develop the potential use of these automatic fruit harvester or harvesting systems is possible. A recent robot which is the closest to commercialization may be a strawberry harvesting robot [1.29]. The robot operates during night time and harvests fruits suspended from the sides of a table top culture in approximately 20 s, yielding a harvest capacity of 0.3 ha greenhouse per night.

Table 1.1: Achievements in fruit harvesting robotics

Fruits	References
Citrus	Schert and Brown [1.3]; Blandini [1.4]; Hayashi and Ueda [1.5]; Recce et al. [1.6]; Brown [1.7]; Hannan and Burks [1.8]; Muscato et al. [1.9]
Apple	D'Esnon and Rabatel [1.10]; D'Esnon et al. [1.11]; Kassay [1.12]; Bulanon et al. [1.13]; Setiawan et al. [1.14]; Zhao et al. [1.15]
Tomato	Kawamura et al. [1.16]; Kawamura et al. [1.17]; Kondo et al. [1.18]; Kondo et al. [1.19]; Monta et al. [1.20]; Kondo et al. [1.21]
Cucumber	Amaha et al. [1.22]; Arima et al. [1.23]; Van Henten et al. [1.24]; Van Henten et al. [1.25]; Tang et al. [1.26]
Strawberry	Ceccarelli et al. [1.27]; Arima et al. [1.28]; Kondo et al. [1.29]; Hayashi et al. [1.30]
Melon	Benady, et al. [1.31]; Benady and Miles [1.32]; Edan and Miles [1.33]; Y. Edan [1.34]
Grapes	Sevilla et al. [1.35]; Sevilla and Baylou [1.36]; Monta et al. [1.37]
Sweet pepper	Kitamura and Oka [1.38]; Kitamura and Oka [1.39]
Eggplant	Humburg and Reid [1.40]; Hayashi et al. [1.41];
Mushroom	Tillet [1.42]; Reed et al. [1.43]
Cherry	Tanigaki et al. [1.44]
Kiwifruit	Scarfe et al. [1.45]
Chicories	Foglia and Reina [1.46]

The achievements of researchers listed in above table are only few examples, apart from these examples; there are many other researchers working worldwide on developing autonomous robotic systems for harvesting the fruits. The detailed review on various harvesting systems based on the harvesting methods, based on different machine vision systems and based on various methods in image data analysis on fruit harvesting was given by *Li et al.* [1.47] along with various projects started on automatic fruit harvesting systems and several research issues related with automatic fruit harvesting systems.

1.3 Problem Identification

As mentioned by *Jimenez et al.* [1.48] to obtain the automatic fruit harvesting system in agriculture sector, ideally, three main problems need to be solved: (1) the guidance of the robot through the crops, (2) the location and characterization of the fruit on the trees, and (3) the grasping and detachment of each piece. The first problem is not critical and can be solved using one operator to guide the robot through the crops or adopting line tracing moving base system. The other two problems have received remarkable attention during the last thirty years, although no commercial harvesting robot is available. To solve problems of location and characterization of fruit on trees, an efficient recognition system is required that can locate the fruits on trees with their positional information i.e. the location and orientation of the fruit. Further, the recognition system should be able to locate the occluded or fruits partially covered by leaves in the variable field environment. Also, to solve the problem of grasping and detachment of fruits, an effective gripping and cutting system is required that can harvest the fruits under various conditions without causing any physical damage to the fruit. Moreover, the picking system should be able to handle the soft, delicate fruits during harvesting time with respect to their various shape and size without causing any damage to trees and could able to perform the harvesting operation at higher speed very precisely.

To avoid the physical damage to soft and delicate fruits, manual harvesting is preferred which significantly increases total cost of fruit production. Also, this type of harvesting method is highly labor intensive and inefficient in terms of both economy and time. To perform the intensive manual harvesting, high labor power is required. If the labor population in the agriculture is taken into consideration, then since last few decades, the labor population is decreasing rapidly [1.49]. Figure 1.1 shows the agriculture labor population around the globe from 1980 and predicted until 2020 while Figure 1.2 shows the decreasing trend of agriculture labor population from 1980 and predicted until 2020 in case of Japan.

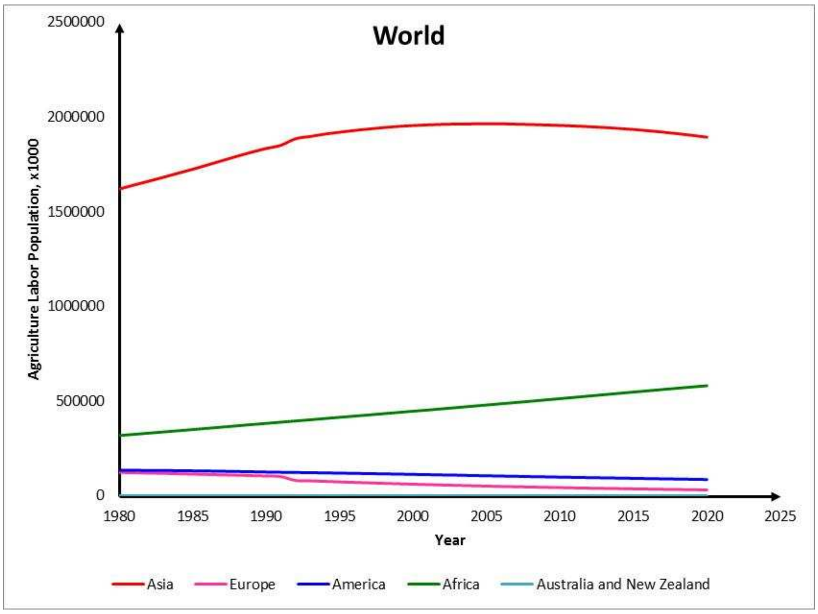


Figure 1.1: Agricultural labor population around the world

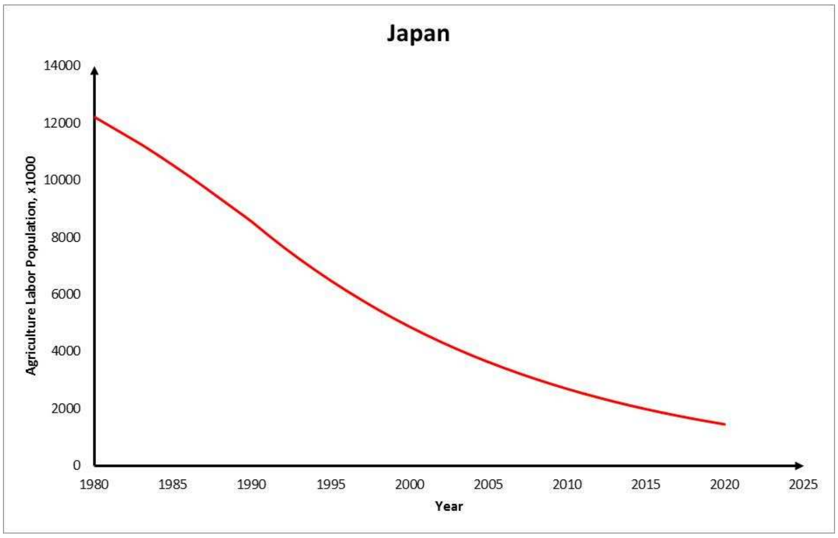


Figure 1.2: Agricultural labor population in Japan

The main reasons for this declining trend of agricultural labor population in the last few decades were major innovations in agriculture and introduction of mechanization and computerization in agriculture around early 90's. As a result, getting adequate agricultural labors to perform the agricultural activities became difficult and thus the labor wages increased rapidly. The higher labor wages adds additional cost to the production cost and hence to the market cost resulting expensive commodities in the market. The use of labor power for agricultural operations also increases the input energy consumption and overall resource utilization on agricultural activities. In addition; there is less agriculture labor power available due to continuous out flow of workers from agriculture to more comfortable and better paying jobs in other industries. At the same time, the high costs of producing food in the developed countries compared to the costs in poorer countries are pushing their growers out of business. Since the cost of labor is constantly rising, the only way to maintain, or reduce labor costs per unit of output is to increase productivity of labor increase the volume of output. Competing on low labor costs is infeasible, given world trade laws and cost of living.

Hence, mechanization is the only answer, since it offers, potentially, the only option for reducing harvesting labor expenses, so that growers can stay competitive in the years ahead and even expands markets [1.50]. Also, mechanization plays a vital role in securing the future of fruit growers in developed countries. Moreover, in addition to providing means for reducing the drudgery of harvest labor and the only solution to harvest productivity, harvest machinery improves the ability of farmers to perform operations in a timely matter. It also reduces the risks associated with the need for large amounts of seasonal hand labor for short periods of time and lessens the social problems, which accompany excessive influx of low-wage workers. Finally, harvest mechanization can also potentially reduce human contact with food and thus reduce contamination possibilities. The machine harvesting systems are a partial solution to overcome these issues by removing fruits from the trees efficiently thus to reduce the harvesting cost to about 35 - 45% of the total production cost [1.51] and helps to save the labor cost, input harvesting energy consumption and to improve the resource utilization on agricultural activities [1.52]. Thus, by considering the facts mentioned above and by understanding the need of efficient and effective harvesting systems, the research was carried out which is presented in this dissertation.

Japan is well known for high tech and sophisticated agriculture food production even though the agricultural labor power is less compared with other countries. This is possible due to only mechanization and atomization of agriculture sector which can be seen by various attempts made by previous researchers to introduce the atomization in various agricultural activities. Table 1.2 shows the major fruit vegetables produced in

Japan while Figure 1.3 shows the status of sweet pepper production in Japan for last few years.

Table 1.2: Major fruit vegetable production in Japan [1.53]

Production year	Onions	Tomatoes	Cucumber	Eggplants	Sweet peppers	Taros
2009	1154	718	620	349	143	182
2010	1047	691	588	330	137	168
2011	1066	703	585	322	142	-
2011/ 2010 (%)	101.8	101.7	99.5	97.6	103.6	-

(Unit: 1,000 t)

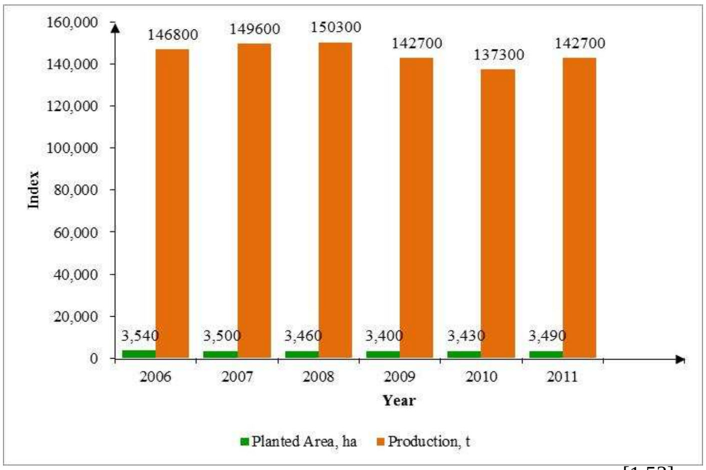


Figure 1.3: Sweet pepper production in Japan [1.53]

In Japan, green sweet pepper is the 5th most important and valuable fruit vegetable grown on approximately 3490 hector area of land producing 142,700 t yield [1.53] which needs not only high man power but also high input energy consumption and high resource utilization during harvesting operation leading to increase in labor cost and production cost [1.54]. This issue is also related with decreasing population of Japan in recent decades [1.55]. On the other hand, detection of fruits in natural background is difficult when color of fruits and background, such as the leaves and stems or fruits, are similarly greenish. As both, green sweet pepper and leaves has almost same color and due to that it is very difficult to recognize them separately during automatic harvesting. The numerous research studies have been carried out on recognition system for major fruit vegetables based on different feature attributes like shape, size, color, edge etc. But in case of green sweet peppers, all these feature attribute parameters are not accountable during recognition operation. Thus, by considering these issues, a green sweet pepper was selected for the research study.

1.4 Objectives

This research study mainly focused on picking and recognition system of green sweet peppers. The main objective of this research study was to design and develop various automatic harvesting systems for green sweet peppers in greenhouse horticulture and to evaluate the performance of each system individually. Detailed specific objectives according to the each harvesting systems are listed as follows,

1. Picking System

1.1 To design the models of various picking systems and test them by simulating and validating under real time variable field conditions to obtain the optimal prototyping parameters before constructing the experimental prototypes.

1.2 The Picking system should be able to grasp and cut each fruit under various conditions like: single fruit, occluded fruits, fruits partially covered by leaves.

1.3 The picking system should avoid any physical damage to the soft and delicate fruits during harvesting operation.

1.4 The grasping and cutting operation should be precise and should work at high speed with high working cycles.

1.5 The picking system should be compact, lightweight, efficient and easy to control and communicate with harvesting robot manipulator.

1.6 To develop the technique for picking system so that there would not be any viral and fungal transformation during harvesting which would help to increase the shelf life period and quality of perishable fruits.

2. Recognition System

2.1 The recognition system should be able to recognize and locate the fruits under conditions like: single fruit, fruits with leaves, fruits with leaves and stem.

2.2 The technique should be applicable in the situations where certain areas of the fruits are not visible due to partial occlusion by leaves or by overlapping fruits.

2.3 The recognition system should be robust enough for operating in the presence of difficult and variable field conditions like bright light reflections, shadows, variable lighting conditions, night operations and noisy background.

2.4 The recognition system output must supply the 3-dimensional position of the recognized fruit.

2.5 The developed algorithm must operate in real-time in a general purpose sequential processor the support of special image processing boards.

2.6 To evaluate the performance of algorithm used for recognition of green sweet peppers and recognition rate by using same recognition system.

2.7 To develop multispectral recognition system to detect the sweet peppers under various selected conditions such as single fruit only, fruits with leaves, partially overlapped fruits and partially overlapped and partially covered fruits.

2.8 To develop and test the algorithm for multispectral recognition system to determine the maturity stage of detected fruits so that only matured fruits should be harvested.

1.5 Scope and Limitations of Research

The mechanization and atomization of fruit harvesting systems can help as labor aids and facilitate the harvesting and picking work, labor-saving machines or mass harvesting systems that improve productivity and reduce labor power by robotic harvesting or automation. The research study presented in this dissertation is basically focused on green sweet peppers but the same harvesting systems can be adopted for various another fruits and vegetables with some modifications in each system. The recognition system is as important integral part of harvesting system which might need special attention when adopting for another fruits and vegetables. The thermal picking system presented in chapter 5, if adopted for another fruits and vegetables, it will help to increase the shelf life and quality of the products and can be preserved for longer time at normal room temperature when compared with conventional cutting methods. This research study may provide partial or permanent solutions, new guidelines towards the probable solutions to the several problems mentioned in the section 1.3

On the other hand, this research will also have some limitations and need to be taken into account in order to link the different harvesting systems and results and discussion derived from the experimental data. It is very difficult and complicated to automate the harvesting operation in greenhouse as it is very intricate process, involving a multitude of tasks which require dynamic, real-time interpretation of the environment and execution of various sensing-dependent operations. While the schematic analysis of harvesting robot manipulator may seems rather straightforward, it requires the integration of a host of technologies, which are at the cutting edge of our knowledge today such as machine vision system, image processing, robot kinematics, sensors, controls, work process flow controlling, programming and communication skills and computerized signal analysis. For adoption, utilization and application of these technologies in robotic harvesting, the cost of final product might be high making the harvesting robot quite expensive at commercialization stage. Moreover, at research level, the system might face failure sometimes due to inadequate developments in the variable field condition environment such as inadequate fruit detection or inability to reach and detach all the recognized fruits.

1.6 Organization of Dissertation

Chapter 1: Introduction – this chapter gives an insight into the background and present status of robotic harvesting, the latest achievements achieved by some researchers, the justification of this research study and need of effective and efficient harvesting systems for sweet peppers in greenhouse horticulture. Further, this chapter also explains the detailed objectives of this research along with scope and limitation that might rise up during research activities.

Chapter 2: Structure of Harvesting Robot – this chapter explains the whole architecture of the harvesting robot. The detailed description on dependent and independent parameter classification, determining the integral parameters that will affect the performance, how to find out the optimal parameters and what should be the design strategies during designing process can be found in this chapter. The prototyping environment was explained along with various subsystems, components and flow charts. Finally, each system in sweet pepper harvesting robot is explained briefly.

Chapter 3: Picking System I – this chapter mainly focused on modeling, simulation and validation of picking system which helps to determine the optimal parameters and component structure for the picking system prototype. Modeling and simulating before prototype construction offers many advantages including selection of components, parameter selections, materials and working mechanism decision and also to test the performance of the simulated model under real-time conditions. Designing the developing the picking system by this way helps to save cost and time. The simulation results and performance test evaluation results along with discussion can be found in this chapter.

Chapter 4: Picking System II – the application of thermal cutting technique in picking system was explained in this chapter. The main objective of this chapter to develop efficient and effective picking system that will be able to perform the harvesting operation and so help to increase the shelf life and quality of fruits. Two different types of prototypes based on voltage and current are discussed in this chapter along with respective experimental results. The chapter further concludes that thermal cutting system helps to increase the shelf life and quality of fruits by avoiding viral and fungal transformation and can be preserved longer at normal room temperature.

Chapter 5: Recognition System I – this chapter explains the color camera recognition system which includes various sensing components, recognition algorithms and feature attribute parameter extraction for harvesting purpose. The chapter enlightens the steps involved in image processing, how to differentiate green sweet pepper, stems and leaves in natural background with numerous color space models. Further, the process involved in obtaining the positional information i.e. *X*, *Y* and *Z* axis coordinates of detected fruit and orientation of detected fruit is illustrated with several figures.

Chapter 6: Recognition System II – this chapter focused on multispectral infrared imaging recognition system for detection of green sweet peppers. The main objective of this chapter was to use multispectral imaging not only for detection but also for maturity decision. This multispectral recognition system will help to decide the maturity of detected fruits so only matured fruits can be harvested. This chapter explains the procedure, analysis of developed algorithms to detect the sweet peppers and decide the maturity stage of detected fruits.

Chapter 7: Conclusions – this chapter highlights the intensive and concrete conclusions withdrawn from analysis and processing of experimental data of research study. This chapter provides only selected brief conclusions; the detailed conclusions for each system can be found at the end of conclusions section of respective chapters. Furthermore, few suggestions and recommendations are given at the end of respective chapters to improve or enhance the research study results if any.

Chapter II

STRUCTURE OF HARVESTING ROBOT

2. Structure of Harvesting Robot

This chapter highlights the structure of harvesting robot, architecture and main units of robot, design considerations and parameters with few designs models and inclined trellis training system adopted to grow the sweet peppers in greenhouse to test the performance of each designed and developed system.

2.1 The Optimal Design Subsystem

The role of this subsystem was to assist in designing process to determine the optimal configuration and parameters given some task specifications and some of the parameters. The following sections describe the required tasked to be done to accomplish this part along with some design strategies.

2.1.1 Constructing the Optimization Problem

Any optimization problem has three main components: objective function to be minimized or maximized, optimization variables and set of constraints. A set of objective functions that can be used in the optimization problem were specified. This set will form the database for the formation of the final objective functions for some of the parameters using the task specification and the performance requirements. Some of the criteria that can be used to form objective functions were:

1. Workspace
2. Manipulability
3. Speed
4. Accuracy
5. Power consumption of motors

In addition to these quantitative measures, there are some rules and assumptions that need to consider to solve the parameters and to give guidance during the design cycle. Some of the assumptions made to simplify the problem were:

1. The robot type and the degree of freedom are given

2. Only revolute joints are considered
3. The links are uniform with rectangular cross section
4. There is a finite set of material used to build the robot with known densities
5. There are finite number of actuators and sensors with known specifications that can be used in the design

These quantitative measures, rules and assumptions can be used as objective functions for some of design parameters from robot specifications.

2.1.2 Design Strategies

During designing, when the performance requirements were stated which form one or more objective functions, a set of constraints were formed from the given specifications, the parameters to be determined for optimal performance were specified and finally the strategy for solving the problem were explained. An example of design strategy is given in Table 2.1.

Table 2.1: Design strategy example

Performance criteria	**Optimization**	**Constraints**
Efficient link lengths	Link lengths	Total link lengths
Maximum manipulability	Link masses	Link lengths, masses
Minimum position error	Feedback gains	Maximum torque available
Maximum speed	Joint friction	Feedback frequency
Maximum acceleration	Joint connection	Motor parameters
Minimum power consumption	Sensor locations	Sensor range
Maximum accuracy	Work cycle	Maximum computer speed
Maximum repeatability	Cost	Maximum communication speed

The strategies for solving the optimization problem will be to divide it into stages, at each stage solve for some of the parameters, then use the values obtained for these parameters in the succeeding stage. By defining some of the parameters before solving the system for other parameters would be helpful in designing cycle. The flow chart of designing cycle is presented in Figure 2.1.

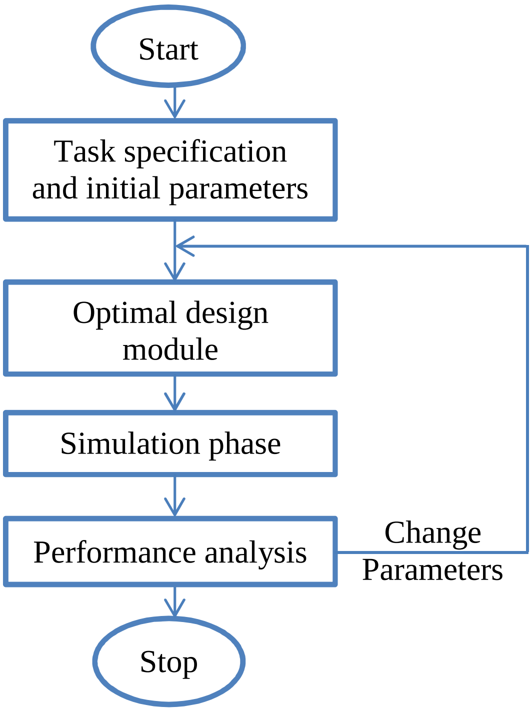


Figure 2.1: The optimal design cycle

2.2 Prototyping Environment

The prototyping environment consists of several subsystems such as:

- Design
- Simulation
- Control
- Monitoring
- Hardware selection
- Modeling – CAD/CAM/Solidworks/ProE
- Part ordering
- Physical assembly
- Performance testing and evaluation

Figure 2.2 shows a schematic view of prototyping environment with its subsystems and interface. These subsystems share many parameters and information. To obtain the integrity and consistency of the whole system, a central interface is necessary with required rules and assumptions for passing the information. This interface will be the layer between robot prototype and subsystems and it will also serve as a communication channel between different subsystems. The main functions of interface are to store set of data, information, generate communication layers, update the information, and control the systems and subsystems.

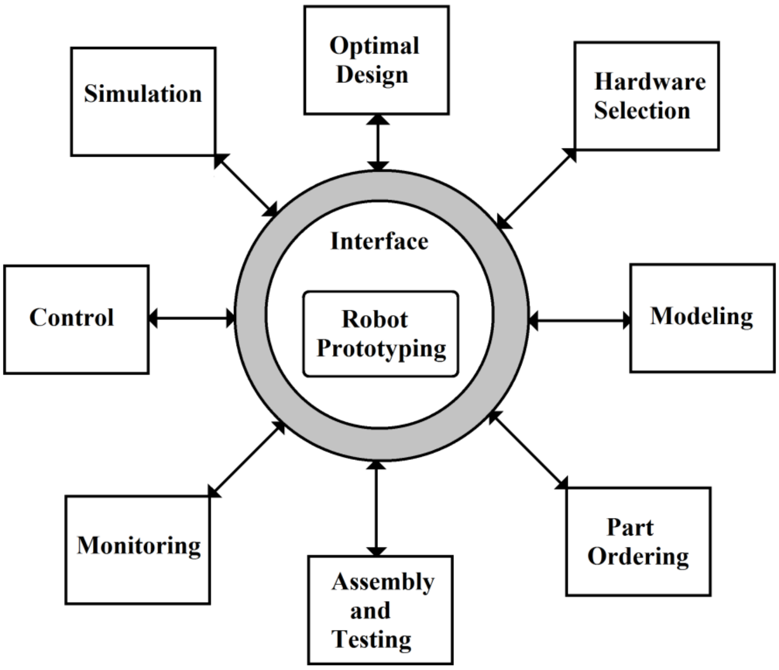


Figure 2.2: Robot prototyping environment

2.3 Prototyping Environment Database

A database for system components and design parameters is necessary to enable the central interface to check the constraints, to apply the update rules, to identify the subsystems that should be informed when any change take place in the system and to supply the required reports. This database contains following components:

- Robot configuration
- Design parameters
- Available platforms
- Design constraints
- Subsystem information
- Update rules
- General information about system

Figure 2.3 shows the top view of the main components in the prototyping environment and Figure 2.4 shows one of these components in details.

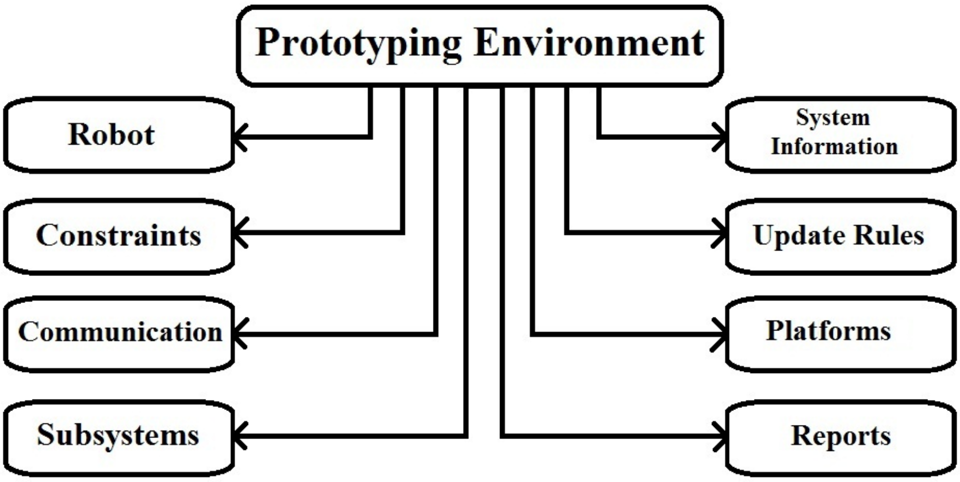


Figure 2.3: The main components of robot prototyping environment

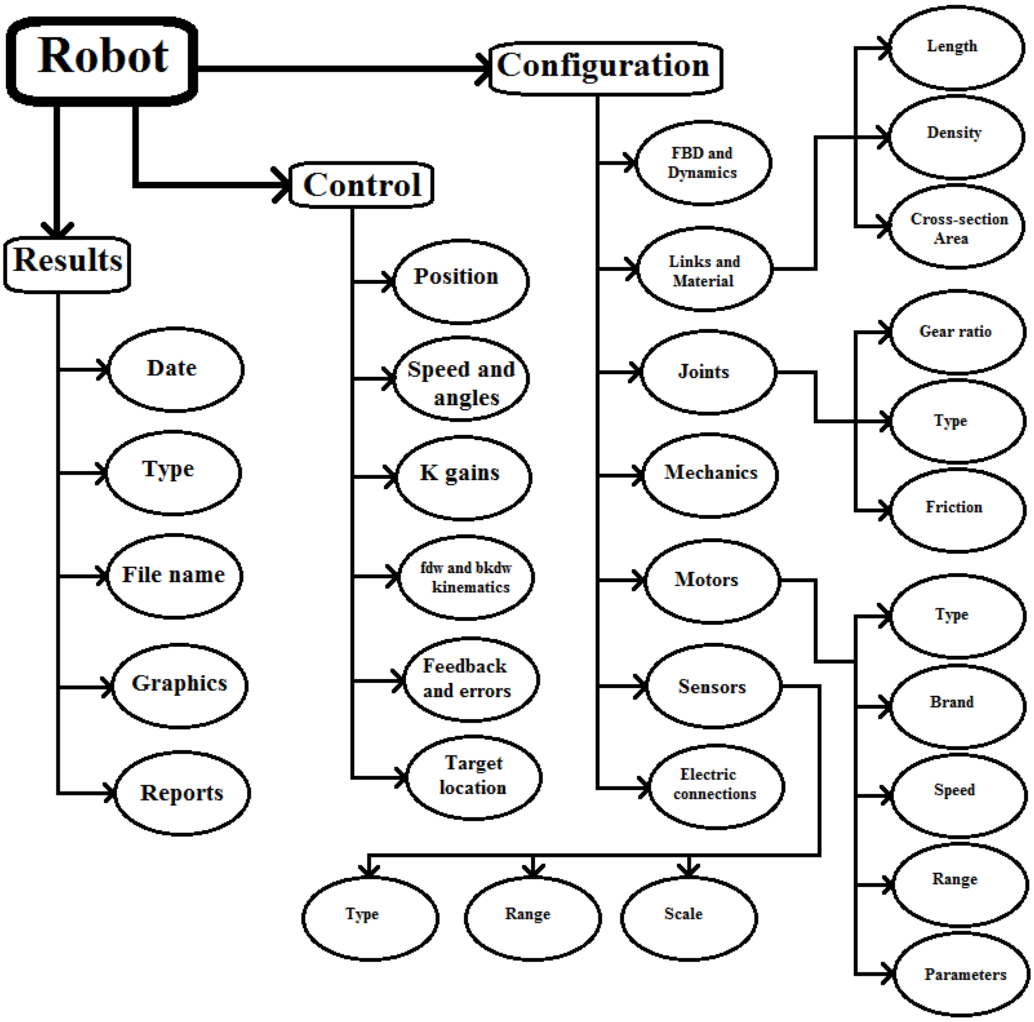


Figure 2.4: Detailed analysis for robot classes

2.4 Overview of Harvesting Robot

To perform harvesting operation of sweet peppers inside greenhouse, the design of robot must be simple, compact and precise. By considering this fact, the robot was designed which can be seen in Figure 2.5.

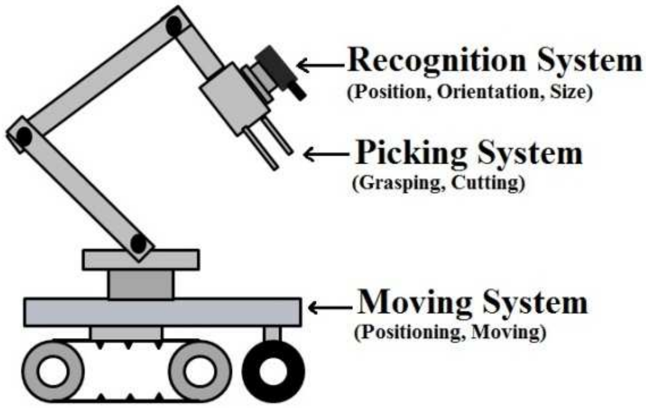


Figure 2.5: Overview of harvesting robot

The harvesting robot composed of three main units and every unit was designed by considering the basic requirements to perform the harvesting operation. At the same time, cost of construction, efficiency of each component, working mechanisms, material selection and working accuracy of each unit was also taken into account. Each unit of harvesting robot is discussed below.

2.4.1 Moving System

The moving system consists of crawling tracks and wheels which forms a base. This base provides a rigid platform to mount the robot manipulator on it. The moving system was equipped with line tracing system that allows moving the robot base inside the greenhouse without any difficulties. For this purpose, each furrow needs a line track laid before harvesting operation starts. The moving system was controlled by S-box and a control program developed in Matlab. The wheels attached with crawler helps at the end of furrows to make a good turning when moving system changing the furrow. The developed program allows base to stay standby until the commands received from manipulator control unit to move forward or backward. The main function of the moving system was to position the robot manipulator relatively according to location of the sweet peppers on trees and move the manipulator whenever necessary.

2.4.2 Recognition System

The main function of recognition system was to find out the location and orientation of the sweet peppers on trees. In recognition system, two CCD cameras along with artificial lightening system were used to capture the real-time images in greenhouse. The captured images were transferred to computer through image grabber interface and further processed in the Halcon image processing software. The recognition of sweet peppers involved several steps during image processing. An algorithm was developed to perform the image processing steps continuously based on binarization of *HSV* color space model. The software can detect the fruits by using light reflection feature. The software provides 3D location and orientation of fruit, stem inclination with respect to fruit, stem length and a center reference point. This positional information data were stored in the computer and further directed to the main robot control program.

2.4.3 Picking System

The picking system consists of gripping and cutting units attached at the end of robot manipulator. The main function of picking system was to grasp the fruits and cut them accordingly without causing any physical damage to fruits. The positional information obtained from recognition system was used by main control program and according to the target location; the movement of robot manipulator takes place. When the end-effector reaches near the target location; the central reference point obtained during image processing defines the grasping points. The gripping unit then grasps the fruit and cutting unit cut the fruit stem according to set length of stem cut. The main purpose of gripper was not only to grasp the fruit but also to avoid any physical damage to the fruit. The opening-closing of gripping unit and cutting process were performed with the help of servo motors which offers high speed, high accuracy and precise movement during the control of end-effector.

2.5 Architecture of Harvesting Robot

The structural design of the harvesting robot consists of one *Oriental* step up motor for base, two *Maxon* motors for arm and one *Kondo* servo motor for picking unit. All the motors were connected to computer through motor controller and Universal Serial Bus. The selection of motors for manipulator was done based on kinematics and dynamic analysis of the robot. Two CCD cameras with artificial lightening around camera neck were connected to the computer via image frame grabber to capture the real-time images. The robot control system composed of several application programs linked with each other. The robot control program and user interface graphic window was developed in *Visual Basic C++* version 6. The architecture of the harvesting robot is demonstrated in Figure 2.6.

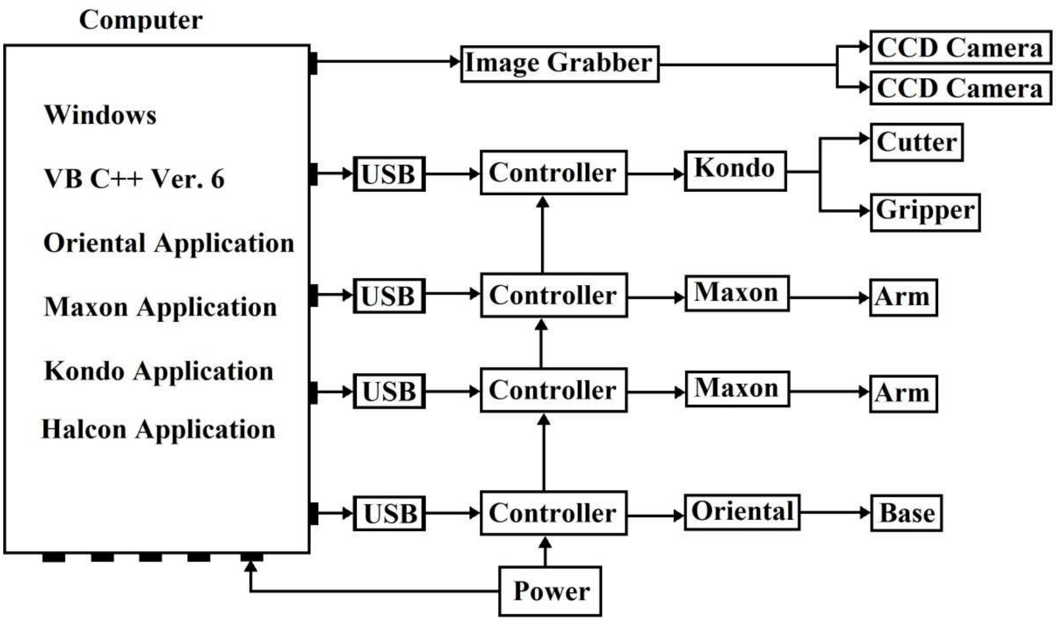


Figure 2.6: Architecture of harvesting robot

The graphical user interface window of control program offers two ways of control mode; manual and automatic. In manual control mode, the manipulator could be controlled by operator by inputting desired position values while in automatic control mode, the movement of manipulator takes place automatically without interference of human. All the harvesting operations in this mode carried out automatically by control program. The program also provides emergency stop of manipulator to avoid any accidents under circumstances of risky environment.

2.6 Inclined Trellis Training System in Greenhouse

The harvesting equipment can operate at maximum productivity when the workspace has been organized to minimize inefficient obstacles, standardize fruit presentation, provide sufficient alleyways and maximize fruit density on uniform growth planes. Certain tree species and even certain varieties within species have an optimal subsistence are for best fruit production, which provides a proper ratio between the number of leaves needed to produce carbohydrates and other organic compounds, and the number of developing fruits [2.1]. The woody mass-roots, trunks, scaffolds and branches supports the tress canopy but contributes minimally towards fruit development once nutrient uptake and moisture demands are met. However, the woody mass continues to use the resources from tree to maintain itself, offering obstructions to robotic harvesting. *Ben-Tal* [2.2] suggested that maximum yield per unit area would be achieved by a large number of relatively small trees, suggesting that smaller robotic systems may actually provide a better economic return.

In the conventional plant training system, sweet pepper plant grows in upward direction and leaves cover most of canopy area which results in difficulties for fruit recognition and manipulator movement. Unlike the human eyes, a robot with visual sensor cannot distinguish one object with a certain color from another object with a similar color and determine the shape of an object; may not be able to detect fruit which is entirely or partly covered by the leaves. In addition to this, the stems and leaves are more likely to become obstacles when the manipulator tries to approach the fruit [2.3].

The advanced plant training system helps to solve these problems by separating fruits easily from leaves and stems. The use of strands or threads helps the plants to grow in almost Y-shape which makes convenient to harvest sweet peppers without any obstacles, reduces recognition errors and smooth movement of manipulator. The wide distance between furrow and ridges helps for easy and smooth operation of moving system.

According to *Juste and Sevilla* [2.4], the configuration of the trees significantly alters the percentage of visible fruits on the tree. For tree row configurations, with a hedge appearance, the visibility of the fruit can reach 75%-80% of the actual number of fruits which is much better than the 40%-50% of visibility for conventional plantings. Figure 2.7 represents inclined trellis training system in greenhouse adopted to grow the sweet pepper plants.

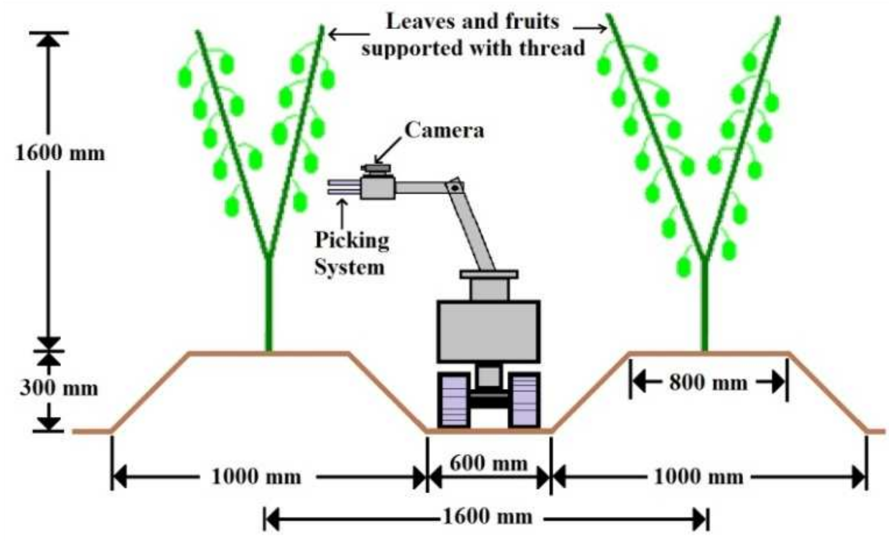


Figure 2.7: Inclined trellis training system adopted in greenhouse

Chapter III

PICKING SYSTEM: I

3. PICKING SYSTEM – 1

This chapter describes the design considerations of picking system, modeling and simulation fundamentals of designed system, prototyping and experiments with picking system that validates the designed model.

3.1 Introduction

3.1.1 Background

The development in the technology leads to wide applications of industrial robots in a large number of areas such as assembly, material handling and machine tending, packing, picking, palletizing, gluing and sealing, arc welding, spot welding, painting and coating, foundry applications and water jet cutting. The application of robots and robotic manipulators in Agriculture is very common in these days; especially, the modern high-tech greenhouses are always equipped with automatic machines and control systems which are derived versions of numerically controlled machines. Fruit harvesting is one of the important application in green house horticulture that helps to save labor cost, input harvesting energy consumption and to improve the resource utilization [3.1-3.3]. Robot gripper is the main functional part of robot arm that helps to grasp the fruit and then cut accordingly. It can also be used for pick and place, packing or welding operations. In agricultural harvesting many researchers are engaged to design robotic devices for efficient and delicate agricultural product picking and handling as the agricultural production rates are significantly influenced by utilization of robots and tools and techniques used in decision support system [3.4]. *Chen* [3.5] mentioned different gripping mechanisms with several parameters and also gave a detailed classification of the grippers based on pair elements used in their construction as linkage, gear and rack, cam, screw, rope and pulley types and miscellaneous. *Sarig* [3.6] described a brief review of work carried out in development of fruit harvesting robot from 1982 to 1992 in different countries. This work was focused on the technical development with different aspects of harvesting problems by pointing out the necessities to optimize research and development work required for realization of robotic harvesting. *El-Kalay et al.* [3.7] focused on industrial robot working mechanisms and their workspace. They also described the concentric gripping of cylindrical objects in relation to rack and pinion type grippers. Their work concluded that the rack and pinion type grippers are mechanically unfit for the harsh industrial environment.

To avoid the physical damage to fruits, manual harvesting is preferred which significantly increases the total cost of fruit production. For the efficient mechanical harvesting, the most important part is to design the proper gripper that can handle soft, delicate objects like fruits, with respect to their various shapes and sizes [3.8, 3.9]. The mechanism based on cutting device attached to a tubular arm for picking soft fruits was designed by *Harrell et al.* [3.10] which consists of a rotating lip that detaches the fruit already enclosed in the tube; the fruit then rolls down the tube to a container. A telescopic robot hand design was given by *Irie et al.* [3.11] which include set of DC motors and 3D vision sensor used to grip and cut the *asparagus* plants in greenhouse. This robot arm took 13.9 s and 23.9 s to perform complete harvesting operation. The use of vacuum grippers in delicate fruit harvesting that avoids high air pressure and physical damage to the fruit was tested by *Sarig et al.* [3.12], *Hayashi et al.* [3.13] and *Monta et al.* [3.14] with the help of vacuum technology. This type of grippers shows good results for picking tightly clustered fruits. At the same time, for vacuum grippers, small leakage in the system leads to failure of operation and higher construction and operating cost results in expensive system. In addition, with suction cup and gripper, *van Henten et al.* [3.15] reported use of thermal cutting tool for cucumber harvesting in which cutting was performed by a thermal cutting technique. Though this thermal cutting operation has several advantages over bacterial transfer, it needs precise system control. *Chambers et al.* [3.16] developed hydraulic gripper and moving jack used to move the heavy structures and for heavy payloads. Though they provide high strength and high speed operations; these types of grippers required large floor space and precise control over the system. The miniature gripping device was proposed for laparoscopic operations by *Morra et al.* [3.17] and *Carbone et al.* [3.18] but they encountered the problem of maintaining high pressure inside the master chamber which actuates the rest of mechanism. *Kondo et al.* [3.19] developed an end-effector to harvest tomato clusters based on force sensing principle operated by couple of servo motors and air cylinder in which the main stem of tree was detected by photo sensor and the peduncle of tomato cluster was detected by strain gauges mounted on grippers. An end-effector took 15 s to perform harvesting operation of a single tomato cluster. The developed end-effector was failed to extend into plant canopy area where node lengths in the high-density system were too short for the end-effector to grasp the main stem near the tomato cluster which results in overall harvesting success rate of end-effector as 50%.

3.1.2 Problem Identification

To overcome the problems encountered by previous researchers, several researchers have developed robot grippers that operate with the help of electric motors and these types of grippers were found suitable for several applications [3.4–3.15, 3.19–3.20]. Most of the robot end-effector uses one electric motor for gripping and one for cutting operation and during programming the control system, each motor needs separate control. This makes the system complicated to program when the whole robot control system program is considered and requires specific attention. Also, using two motors for gripping and cutting unit increases the cost according to the application. Thus, by considering the need of simple and economical gripper, this research was carried out to design gripping and cutting system that operate with only one electric motor which would reduce complications in programming and operation.

This chapter also focuses on different aspects of modelling the prototype with various design parameters and different characteristics of kinematic and dynamic performances. To obtain the optimal parameters that would enhance the performance and at the same time, prototype could be simulated before manufacturing so that if there would be any faults or failure within the system then it could be replaced during simulation. This helps to reduce the time over the traditional error and trial design method and also it saves the cost of manufacturing by providing the best options for construction of prototype. This chapter describes the importance of modelling, simulating and validating the prototype by considering design factors, static and dynamic behaviour of the prototype and its performance under various conditions. Developing the suitable model with several design studies and performing simulation of the designed studies provides the optimal design parameters and selection of economical and efficient materials for prototyping the model. The various motions within the model can also be observed during simulation and this could help for designing the control system of the prototype that saves time, cost, defects in the prototype and assure the efficient performance of the designed prototype.

3.2 Picking System Design Considerations

The robot grippers in horticulture applications for fresh fruit and vegetable manipulation have to fulfil some specific requirements such as high speed activation, adaptation to a variety of shapes, maximum adherence and minimal pressure, no damage to the product, low maintenance, high reliability, low weight, be approved for contact with foodstuffs, low energy consumption, required positional precision for both gripping and releasing of the product, ease of cleaning, easy and fast ejection of the product (important for products of low weight). By considering these special requirements and to specify the gripping manipulation, the strategies mentioned by *Blanes et al.* [3.21] were followed to design the picking system for this research. The classification of the manipulation strategies and methods can be seen in Table 3.1.

Table 3.1: Classification of manipulation strategies and methods

Strategy	Method		Handling ability				Damage type			
			Gripping	Positioning	Orienting	Placing	Bruise	Tear	Break	Deformation
Air	Vacuum	Suction cups	Yes	No	No	Yes	Low	Low	Low	Low
		Pipes	Low	Yes	No	Yes	Yes	Yes	Low	Low
	Pressure	Bernoulli	Yes (no contact)	Low	No	Yes	No	Yes	Low	Low
		Blow	No	Yes	Low	Yes	No	No	Low	No
Contact	Gripper	Electric	Yes	No	Yes	Yes	Low	Low	Low	Low
		Pneumatic	Yes	No	Yes	Yes	Low	Low	Low	Low
		Hydraulic	Yes	No	Yes	Yes	Yes	Low	Yes	Yes
		Rubber	Yes	No	No	Yes	No	Low	No	Low
		Robot hands	Yes	No	Yes	Yes	Low	Low	No	No
	Multibody mechanism		Yes	No	Low	Yes	Low	Low	No	Low
Ingressive	Needles		Yes	No	No	Yes	Yes	No	Yes	No
Fluid	Rheological change		Yes	No	Low	Yes	Low	Low	No	Yes
Product properties	Gravity		No	Yes	Low	Yes	Yes	Low	Yes	Yes
	Piling up, pushing		No	Yes	Low	Yes	Yes	Low	Low	Yes
	Dynamic		No	Yes	Low	Yes	Yes	Low	Yes	Yes
	Scooping up		No	Yes	Low	Yes	Low	Yes	No	No
	Vibration		No	Yes	Low	Yes	Yes	Yes	No	No

Thus, by considering the above strategies and detailed review of previous work, a simple comparison was made within electric, pneumatic and hydraulic grippers which offers low damage good results of gripping, positioning and orientation. This comparison would be helpful to decide the design factors and manipulation strategy for picking system in this research. The comparison of electric, pneumatic and hydraulic grippers can be seen in Table 3.2.

Table 3.2: Comparison of electric, pneumatic and hydraulic grippers

Electric Grippers	**Pneumatic Grippers**	**Hydraulic Grippers**
High accuracy and repeatability	Smaller units, quick assembly	High strength and high speed
Less floor space	High cycle rate	Large robots, Takes floor space
Low cost	Easy maintenance	Mechanical Simplicity
Easy maintenance	Needs Precise system control	Used usually for heavy payloads
Good results for single fruits	Good results for cluster fruits	Good results for single fruits

Based on the comparative study on electric grippers, pneumatic grippers and hydraulic grippers, it was decided that the new picking system should be designed based on contact gripping manipulation strategy using electric motor gripper method. In case of sweet peppers, the shape of fruit is irregular and surface is not always smooth which made difficult to consider about pneumatic and hydraulic grippers. As electric gripping method has several advantages over other methods and mostly it is suitable for single fruit harvesting operation, the number of designs were prepared by consider other design parameters essential for efficient picking system.

All the possible interactive factors and input parameters relevant to gripper design were framed together and the steps followed to obtain the optimal gripper design. The factors significantly influence the gripper selection can be seen in Figure 3.1 in which crucial conditions of not only dynamic but also static components were interconnected with the optimal gripper design. The flowchart based on several questions that helps to decide these interactive influencing parameters can be seen in Appendix A: 1.

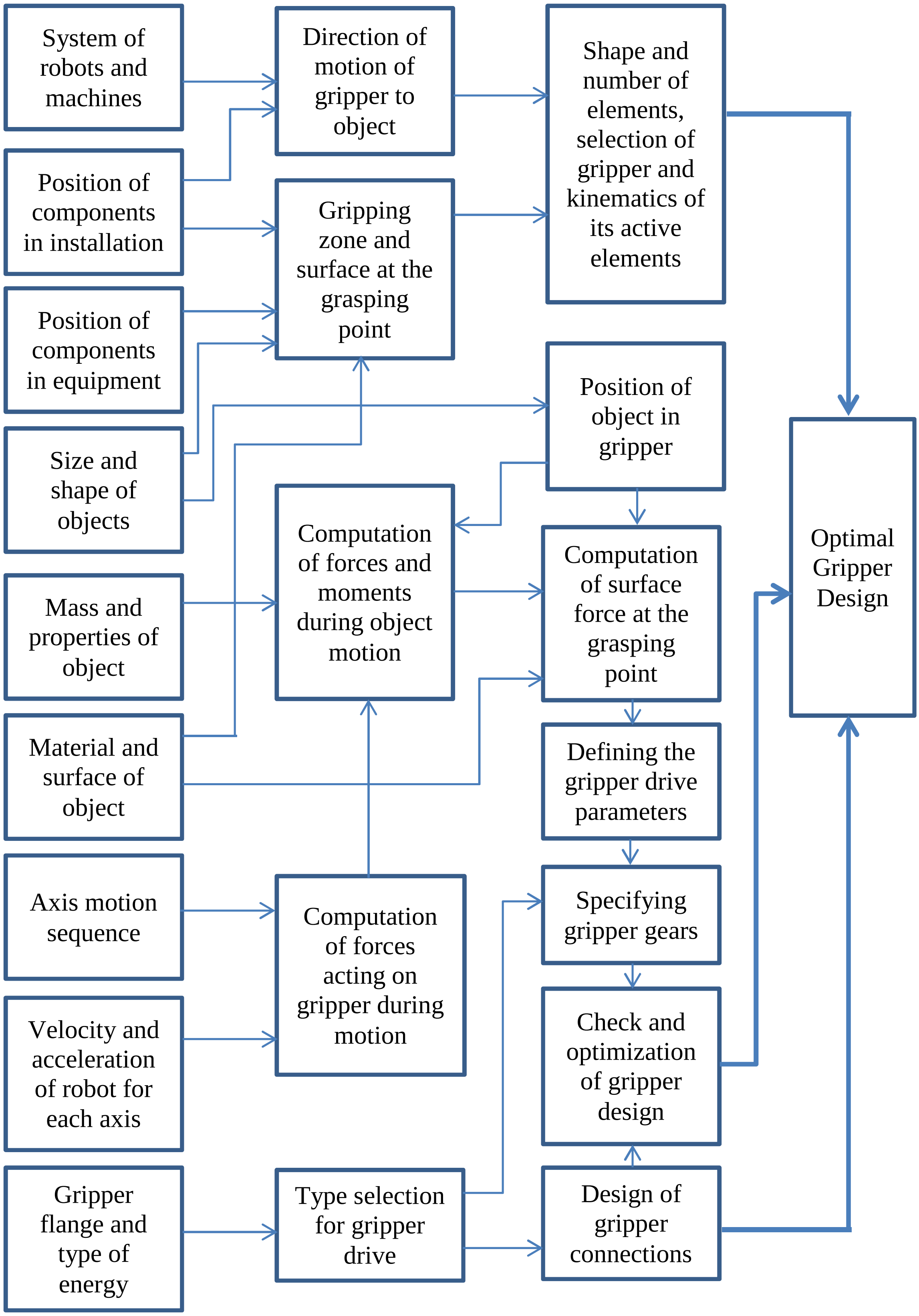


Figure 3.1: Interaction factors and input parameters relevant to optimal gripper design

3.3 Design of Picking System

3.3.1 System Design

The mechanical system to which this chapter represents is a picking and cutting system which composed of two parts; the first part is aimed at grasping the sweet pepper and the second part is aimed at cutting the stem of sweet pepper from the plant. These both parts have been specifically designed with the purpose of imitating the manual operations by labor.

Figure 3.2 shows the concept of new gripping and cutting tool designed to harvest the sweet peppers. In this system, two same size big gears and one small size gear was used. The same size big gears were meshed together and installed on supporting plate with washers and power was provided to one of the big gear through servo motor axis. Further, the small gear was meshed with one of the same size big gear installed previously and a circular disc was attached to the top of small gear axis. A sharp scissor was installed on the circular disc by means of link mechanism so that it can operate through the power provided by servo motor at base shaft.

The gripper was connected to the big gears of same size and cutter was attached on the circular disc. The care was taken that the gripper links should not interfere with small gear when it is in operation. The gripper was fabricated by using small aluminium plates and internal thermo-col coating was applied on the inner sides of plates to avoid any physical damage to the sweet pepper. The gripper bars were attached at root pitch level of the gears and this joint was fixed. In case of cutter, the links were used to connect the scissor and circular disc. The joints where links connect to the scissor were tightened while the joints where links connect to disc were kept loose to rotate freely.

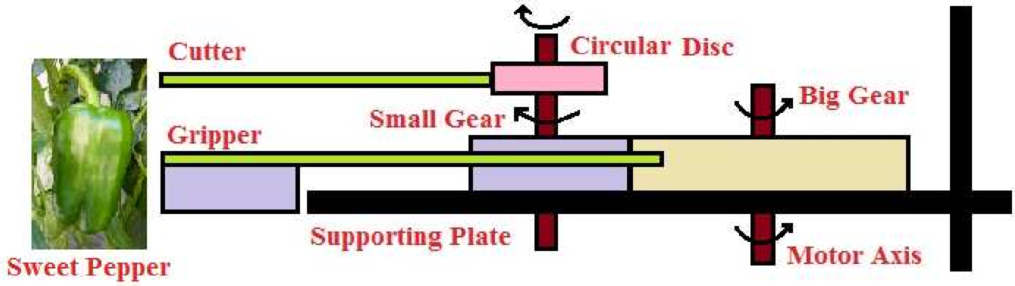


Figure 3.2: Concept of picking tool

3.3.2 System Operating Mechanism

The rotating power from the servo motor was transferred to the big size gears and then to the small gear. The circular disc installed on the axis of small gear rotates with the same speed of small gear while gripper connected to the big gears rotates with the same speed of big gear. The purpose behind using different size gears was to obtain the speed variation in the harvesting operation; that means the gripping speed should be slower than the cutting speed but both gripping and cutting operations should perform simultaneously. This offers good advantage of holding the sweet pepper slightly earlier than cutting the stem.

The gripping system and cutting system were controlled by Kondo *KRS 6003 HV* servo motor [3.22] through computer and whole system was programmed to operate accordingly. The opening - closing of gripper and scissor was controlled by a program which was developed in Visual Basic C++.

When the servo motor rotates, the power from motor shaft was transferred to the big gears which drive the gripper. At the same time, small gear meshed with one of the big gear drive the circular disc installed at other end of axis. Further, the scissor attached to the circular disc starts operating with rotation of disc and the arrangement of disc interacting with scissors can be seen in Figure 3.3. Due to variation in size of holding area and cutting area, these big gears and small gears offers speed variation that helps to hold and cut sweet pepper at the same time.

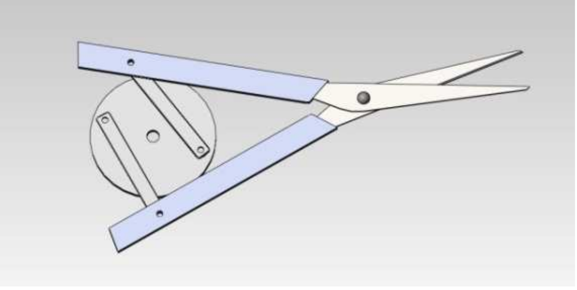


Figure 3.3: Attached scissor on circular disc

3.3.3 Speed Control of the System

Figure 3.4 represents the detailed block diagram of the control system used to operate and control the gripping and cutting system. The control program was written in Visual Basic C++ to interface between servo motor and computer. The servo controller *KCB-1* [3.23] was used to control the Kondo servo motor. The motor rotates by 270^0 without restriction and the program was used to control the rotation of motor in two patterns, first pattern rotates motor by 173.5^0 in slow speed while second pattern rotates motor up to 202.5^0 in fast speed. The first pattern assists in gripping with slow speed while the second pattern facilitates cutting with high speed. Therefore, for complete and successful gripping and cutting of the sweet pepper, motor was programmed to rotate by 202.5^0 with two speed variations.

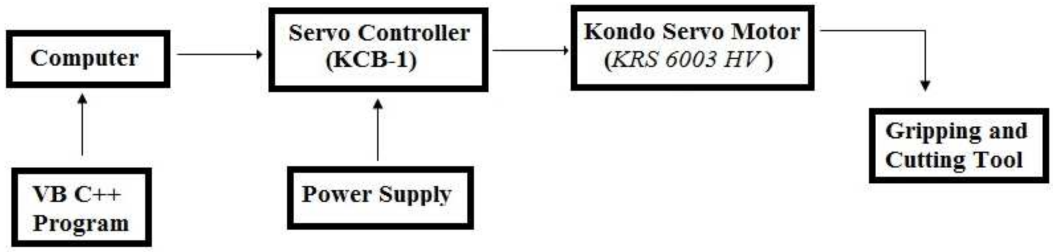


Figure 3.4: Block diagram of speed control of the system

3.3.4 Advantages of Designed Picking System

In the prototype developed by *Kitamura and Oka* [3.20], the gripping system was based on parallel link mechanism which was made by two metal links that causes physical damage to the fruits and cutting system was made from the pruner which fails to cut the stem of fruits when fruits were overlapped. The prototype was sliding rail type timing gear based device which takes time to execute harvesting operation. In proposed design, gripping and cutting operations intended to perform by using only single servo motor to avoid complications in the overall programming system and operation. Also, it helps to save the cost of manufacturing and cost of maintenance. The proposed device can easily be mounted to the harvesting robot developed previously [3.20] and can execute the harvesting operation only in 1.10 s. Furthermore, the proposed device was found very suitable to cut the fruit stem under various conditions including overlapped fruits. In the proposed device design, 10 mm thick layer of thermo-col was applied to the gripper bars to avoid any physical damage to fruits. The thermo-col layout forms an open box container structure which stabilizes the sweet pepper by direct grip and holds fruit stem immovable for cutting operation.

3.4 Modeling of Designed Picking System

The developed model of designed gripping and cutting system can be seen in Figure 3.5. The model was simulated to observe the system behaviour with real parameter environment and to test the system against different kinematic and dynamic performances. The modelling of the system provides all the optimal parameters which were used to build the prototype and improve the system performance.

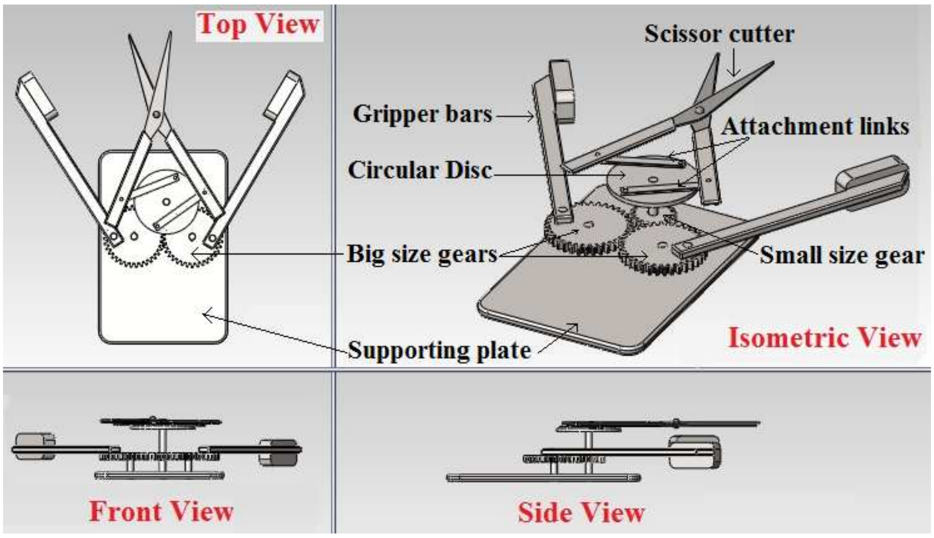


Figure 3.5: Designed system model with different views

3.4.1 Simulation Parameters and Conditions

During the simulation, the forces and torque acting on the model were considered along with all mass properties of the system components and centre of gravity acting centrally downwards to the model. The torque required for gripping and cutting operation by servo motor was computed by dynamic analysis of robot. In the simulation, the rotational torque 1.32 N-m was applied to the motor axis. The grasping force that causes physical damage to the fruits was also calculated by force impact tests. The opposing grasping force 1.603 N was applied to both gripper bars by maintaining the distance between two gripper bars at 50 mm. This distance was considered based on average diameter of matured sweet peppers. The developed gripping and cutting model was tested by means of high quality solid mesh with 4 point Jacobian having 1.06 mm tolerance and total 16626 nodes. The different components were specified with the specific materials and S-N curves so that the actual results can be obtained that would be used to build prototype. For this purpose, the in-built material property libraries were used and to avoid the complications in the simulation, the components were assembled by using the various assembling options available in the software. After successful meshing of the model, it was tested against static characteristics like stress, strain, factor of safety, displacement of the components and design insight and fatigue properties like fatigue - damage, fatigue - load factor and fatigue - life cycle.

3.5 Simulation Results of Model

The model was simulated to obtain the data for static and fatigue studies; that means to check the model for its dynamic physical properties and kinematic performance. The simulation results of gripping and cutting model helps to determine the static and fatigue characteristics and effectiveness of the system. Figure 3.6 represents the component contact and applied rotating torque acting on the gripping system along with center of gravity force acting centrally downward.

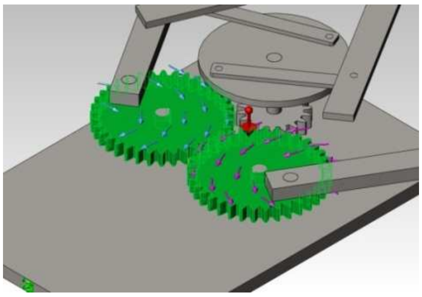


Figure 3.6: System components with acting forces and torque

3.5.1 Static Characteristics

The simulation results for stress on the system were illustrated in Figure 3.7 which indicates clearly that the system supports the stresses developed internally. This also means that the model can tolerate the stresses generated after application of torque and during the operation. Only some part of gripper bar that connects to the gears were observed more stressed than other components. The minimum stress and maximum stresses were recorded as 117.4 N/m^2 and 16.82 x 10^6 N/m^2 respectively which are in safe limits [3.24].

The simulation results for equivalent strain on the system were shown in Figure 3.8 in which it was observed that the gripper bar that connects to the gears were slightly exposed to the strain. The minimum strain and maximum strain were observed as 5.62 x 10^{-10} and 5.94 x 10^{-5} respectively which are negligible values. It means overall system has almost inferior deformation when the external forces applied or during the operation.

The Figure 3.9 shows overall displacement of model in which maximum displacement was found at gripper bars and then at scissor tips; 150 mm and 42 mm respectively. This clearly indicates that gripper bars and scissor tips has supplementary movement in association with gears. Also distinction in displacement confirms that the speed variations of large and small gears which were responsible for movement of gripper bars and scissor tips at different speed. For displacement, drive components that means all gears were not considered as circular movement of those components was restricted by servo motor controller.

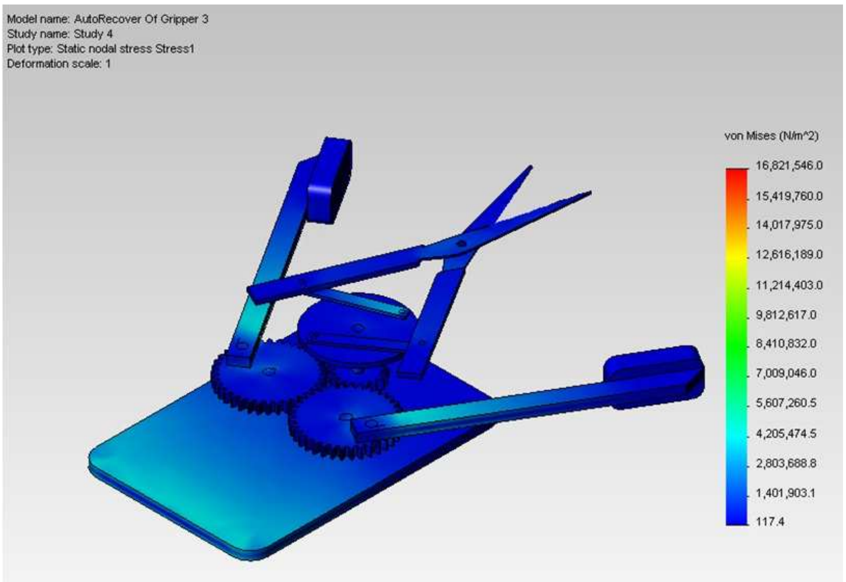


Figure 3.7: Stresses acting on the model

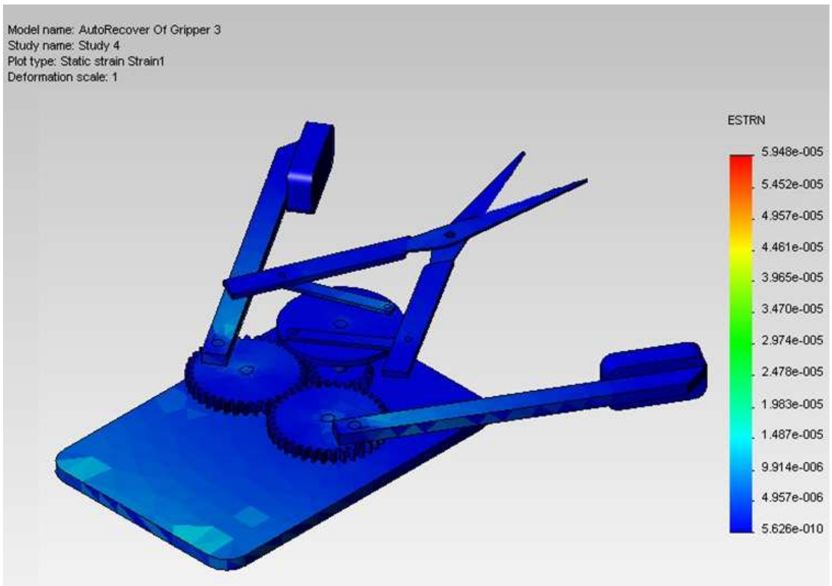


Figure 3.8: Strains acting on the model

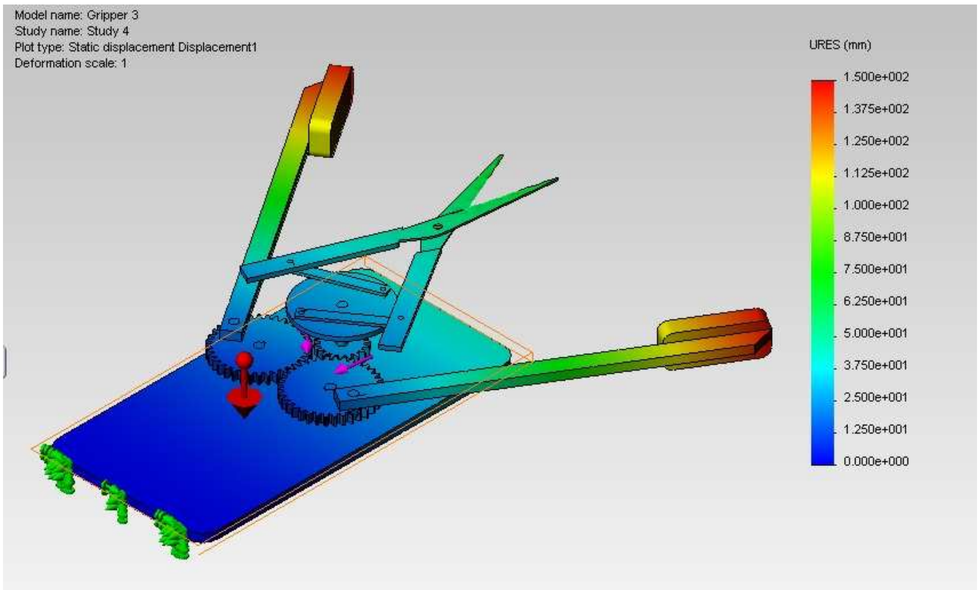


Figure 3.9: Overall displacement of the model

A Design insight plot shows the regions of the model that carry the loads most efficiently with a continuous path between the various forces acting on model as shown in Figure 3.10. Design insight plot helps to replace the system components if any component of the system unable to carry the load efficiently. The model was found significantly strong to carry all the forces acting on it without any modification.

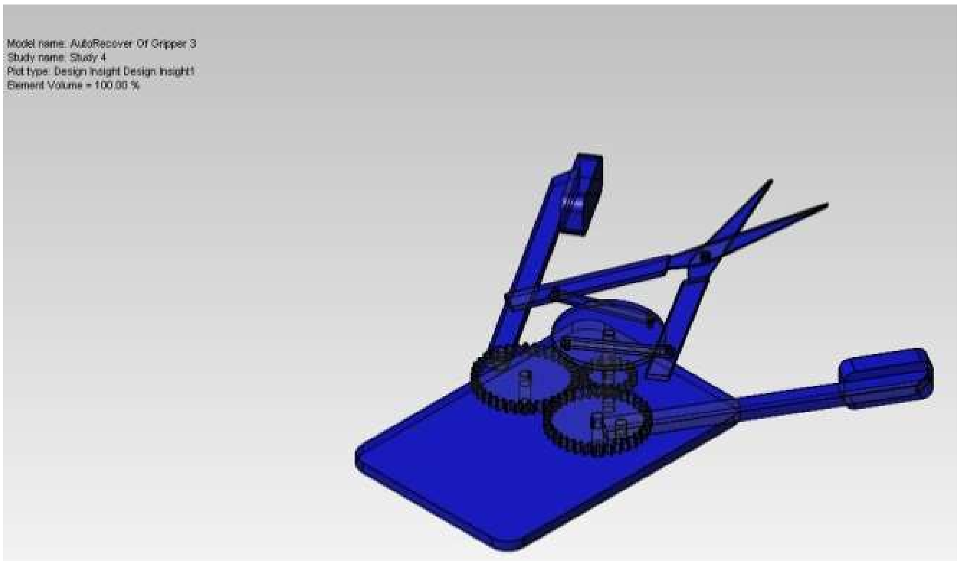


Figure 3.10: Design insight view of the model

3.5.2 Fatigue Characteristics

Figure 3.11 represents the factor of safety plot for the model in which the model was found significantly safe against deformation and buckling effects. It also demonstrates that the structural capacity of a system beyond the expected loads was enormously higher.

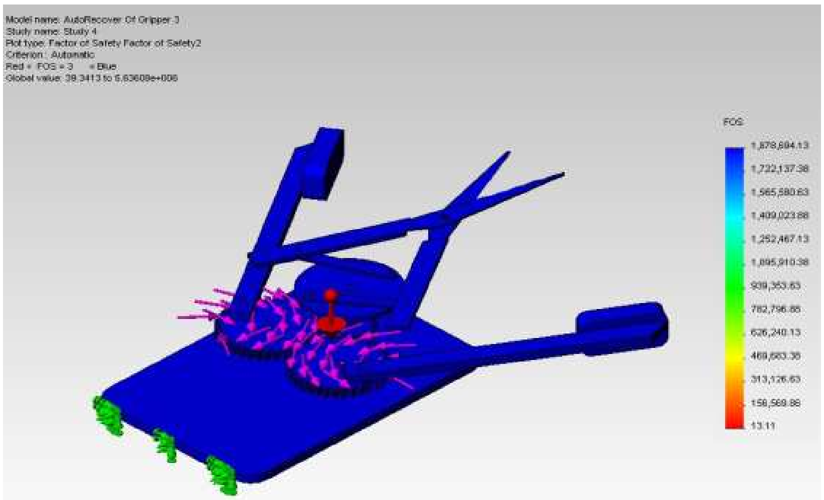


Figure 3.11: Factor of safety plot

The percentage of the life of the structure consumed by the defined fatigue events can be seen in Figure 3.12 in which the percentage damage was found very less for model. The model was fully loaded with 1000 cycles of load during the simulation. This property of the model was found significantly affected by life cycle and can be seen in Figure 3.13. The biaxial ratio was found as 1 which clearly indicates that life cycle of the model affected moderately by performance of system. The biaxial ratio helps to determine a fatigue strength reduction factor.

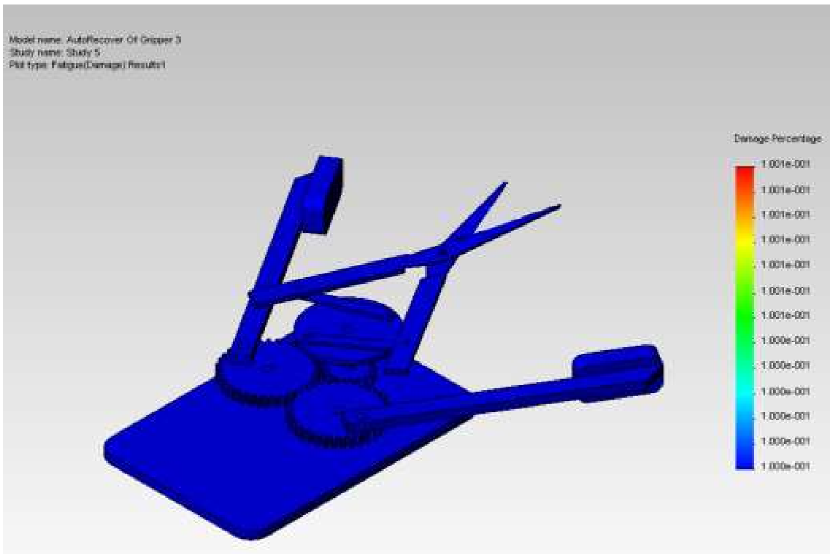


Figure 3.12: Fatigue – damage plot

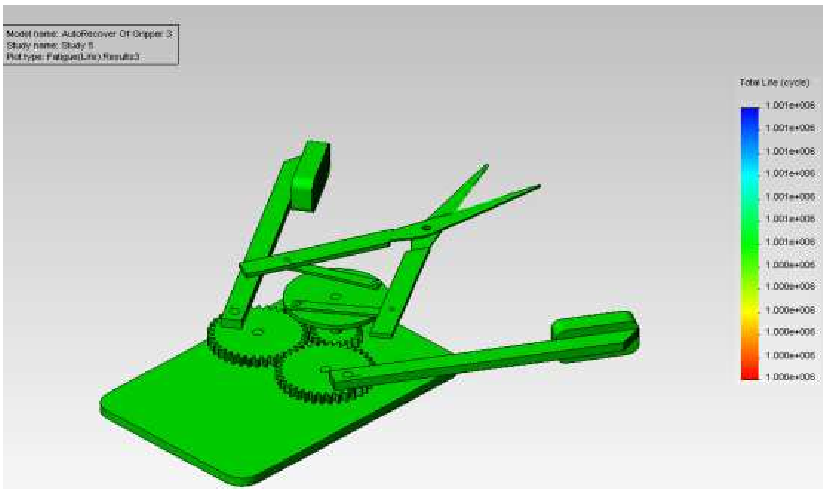


Figure 3.13: Fatigue – life cycle plot

The load factor of safety for fatigue failure at each location was demonstrated by Figure 3.14 in which all the system was exposed to the factor of safety as 3. The load factor less than 1 indicates the failure of the system and in developed model it was found as 5 which confirms the minimum fatigue failure of the model.

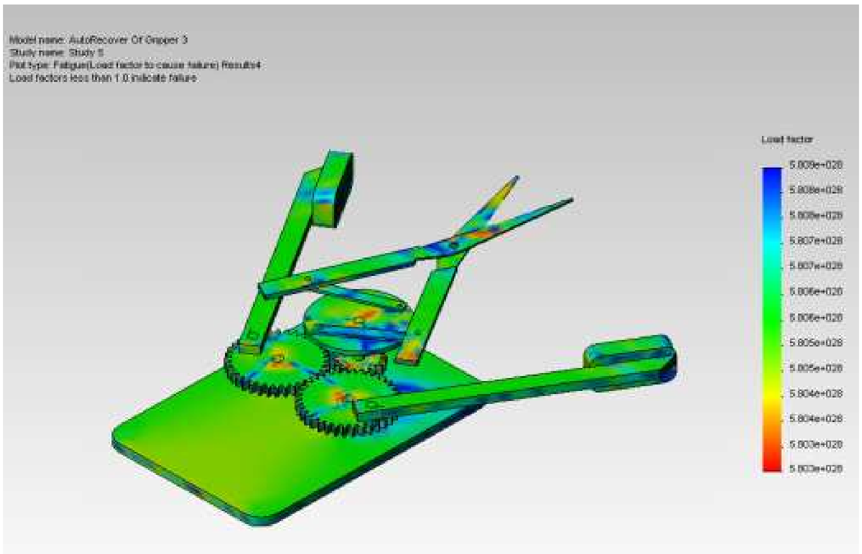


Figure 3.14: Fatigue – load factor plot

The simulation results of the model validate the physical characteristics and properties of the system and confirm its reliability and significant effectiveness of the system. The data obtained during the simulation were used for fabricating the prototype. The static characteristics allow the selection of materials while the fatigue properties help to determine the component structure and reliability of the each component. The optimal parameters like component displacement and design insight properties were found helpful for optimal design of prototype. The distance between gears, attachment of gripper to big gears and attachment of scissor to circular disc were determined by designing several models. The optimal openings of gripper and scissor were determined by driving the model with real conditions of servo motor and torque acting by it on the model. The simulation results presented here were obtained from the optimal model design parameters.

3.6 Experimental Device and Experiments

Based on the results obtained from model, the gripping and cutting prototype was constructed. The plain carbon gears; two of module 2.5 with 36 teeth and one of same module and 18 teeth were used to drive the system with 20^0 pressure angle, 10 mm face width and 10 mm nominal shaft diameter. A 50 mm circular disc was installed on the top of small gear shaft along with scissor as shown in Figure 3.3. Two links were used to connect the circular disc and scissor. The joint that connects scissor and links were tightened while another end of the link which connects to the disc was kept free to rotate. This helps to drive the scissor with rotation of the circular disc. In the prototype, the gripper opening was found exactly same while in case of scissor it was found as 45 mm. The grasping force by gripper was determined by load cell while required torque to perform the operation was calculated by using kinematic and dynamic analysis of the robot hand. In the prototype, another supporting plate was used to maintain the height of the scissor and keep the scissor in horizontal position. The scissor was attached on this new supporting plate and horizontal movement of scissor on the plate was restricted by using screws. The thermo-col coating was applied inside the gripper bars to form a box structure which helps to carry the small sweet peppers during harvesting.

Table 3.3 represents the characteristics and properties of the experimental prototype and components used. To validate and test the performance of prototype, all the material and component properties used to construct the prototype were same as that of properties and characteristics used in simulation model. Further, Figure 3.15 illustrates built prototype with set of components used in the model.

Table 3.3: Configuration of experimental prototype

	Property	**Value**
Gripper (Aluminum 1060-H18)	Degree of Freedom	1 / 2
	Grasp type	Compliant, parallel grasp, force closure
	Maximum opening	150 mm
	Grasping force	1.603 N
	Grasping surface	80 X 45 mm
Cutter (Stainless steel)	Cutting type	Slicing horizontal cut, force closure
	Maximum opening	45 mm
	Cutting tool	Scissor
Motor	Kondo, *KRS 6003HV*	DC servo, 5W
Controller	Kondo, *KCB -1*	6 Serial servo ports, 7 analog input ports and 6 configurable digital I/O ports (4 can be set to PWM output)
Torque	Motor torque	6.57 N-m
	Required torque	1.32 N-m
Gears	Plain carbon (2)	2.5M 36T 20PA 10FW 10NSD
	Plain carbon (1)	2.5M 18T 20PA 10FW 10NSD
Average time to grasp and cut		1.10 s

Side View Top View

Figure 3.15: Experimental prototype

The performance of the developed experimental device was tested and validated by means of adopting the device to grasp and cut the sweet peppers in green house. During the experiments, various features of the sweet peppers were recorded. For the experiments, four different conditions were selected as shown in Figure 3.16.

1. Sweet peppers without leaves 2. Sweet peppers with leaves 3. Partially overlapped sweet peppers 4. Overlapped sweet peppers with leaves

Figure 3.16: Experimental conditions

The purpose behind selecting these conditions was to comfort the new system in previously developed robot prototype by *Kitamura and Oka* [3.20]. Also, almost same conditions were adopted for distinction and recognition of sweet pepper during image processing by *Kitamura et al.* [3.25] and *Kitamura and Oka* [3.26]. So, it was decided that to adopt the same conditions that used to determine the sweet pepper distinction and recognition during the experiments so that the effectiveness and functionality can be determined easily. During each grasping and cutting, the time required to perform the operation was recorded. The depth of stem cut from sweet pepper was supposed to deep so the distance of cutter was adjusted to 40 mm from the gripper. This distance can be increased or decreased by adjusting the shaft of cutter installed on circular disc or making adjustment in height of cut screw that connect scissor and supporting plate. After each harvesting operation different features of the sweet peppers were recorded. To check the practical feasibility of the system, different size and shapes of sweet peppers were used for experiments.

3.7 Results and Discussion

The constructed prototype was tested for the practical application for grasping and cutting the sweet peppers so that the designed prototype model could be validated and confirms the performance. The performance of prototype was found significantly reliable during the experiments. Figures 3.17 to 3.20 shows the pictures taken during the testing of prototype with four different conditions to check the performance of prototype in the field and validate the simulation results obtained from designed model.

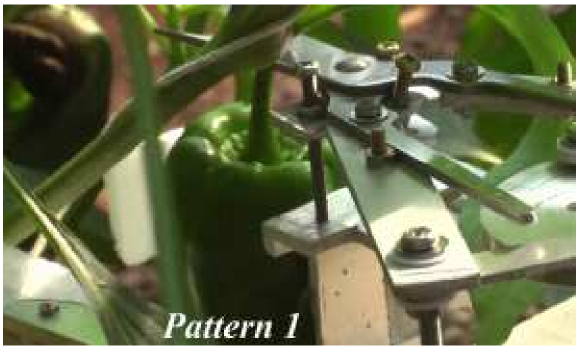


Figure 3.17: Field testing- condition 1

Figure 3.18: Field testing- condition 2

Figure 3.19: Field testing- condition 3

Figure 3.20: Field testing- condition 4

In all four conditions, sweet peppers of big size (2L and L), small size (M and S) and irregular size were tested. The sweet peppers in the greenhouse used for experiments were classified based on their size and weight as illustrated in Table 3.4.

Table 3.4: Classification of sweet peppers

Class	Size	Height, mm	Width, mm	Weight, g	Sample Image
A	2L	above 75	above 55	56 – 80	
	L	55 – 75	45 – 55	41 – 55	
	M	40 – 55	35 – 45	28 – 40	
	S	35 – 40	25 – 35	23 – 27	
Ⓐ	–	less than 35	less than 25	–	

In the 1^{st} and 2^{nd} condition of experiments, the significant performance of the prototype was observed. The grasping and cutting actions were detected smooth and easy. There was no judgment errors found during the harvesting operation and all the samples were harvested successfully. Here, judgment errors were not due to image processing unit or false detection of sweet peppers. The judgment errors occurred in the situations when more than 3 fruits forms cluster together or the fruit stem was twisted around branch of tree. In case of fruit cluster, the stems together forms solid structure and locating right stem of grasped fruit was difficult which results into grasping one fruit and cutting another fruit. In case of twisted stems, it was difficult to perform cutting operation as cutter exposed to fruit stem and small branch together. Though these situations are not common, still there are few chances to encounter these judgment errors. If all the clustered fruits would grasp together or the stem twisted with thin branch, then there are possibilities of successful harvesting operation. In 3^{rd} and 4^{th} conditions, the slight judgment error was observed due to fruit clustering but still the prototype was able to perform harvesting operation. Especially, in 4^{th} condition, the observation was recorded that the two overlapped sweet peppers were grasped but only the first one was exposed to cut by scissor. Also, even the stem was covered with leaves; the cutter cut the stem through the leaves. The performance of the prototype was found satisfactory under 3^{rd} and 4^{th} conditions. As per the results obtained in simulation, none of the system component exposed to deformation and fatigue. Figure 3.21 shows the smoother depth of cut while Figure 3.22 shows the sweet peppers after harvesting under different conditions. None of the harvested sweet peppers were found physically damaged due to direct grasping action by gripper bars; in fact, the thermo-col coating absorbs the grasping force impact during gripping action.

Figure 3.21: Average depth of cut

Figure 3.22: Harvested sweet peppers

During the experiments, all the small size sweet peppers with 4 different conditions were harvested with good results and without any judgment errors. In case of big size sweet peppers, only condition 3 and 4 were faced problem of judgment error but still the device was able to perform the operation successfully. Table 3.5 summarizes the harvesting performance of the device. Under each selected condition, 6 samples were tested to verify the reliability and functionality of the device and validate the simulation results. The numbers in the bracket represents the numbers of test samples out of 6.

Table 3.5: Experimental device performance

	Small Sweet Pepper		**Big Sweet Pepper**	
	Successfully Harvested	Judgment Error	Successfully Harvested	Judgment Error
Condition 1	Yes (6)	No (0)	Yes (6)	No (0)
Condition 2	Yes (6)	No (0)	Yes (6)	No (0)
Condition 3	Yes (6)	No (0)	Yes (6)	Yes (0)
Condition 4	Yes (6)	No (0)	Yes (5)	Yes (1)
Harvested Sweet Peppers = 47				

The average depth of the cut was found 15 mm and out of 48 samples, 47 sweet peppers were harvested successfully. In 4th condition with big size sweet pepper, only one sweet pepper was failed to perform the harvesting operation. This was due to the excess overlapping and judgment error to locate the stem of sweet pepper. The sweet pepper stem was twisted along the thick branch of the tree which results into failure in harvesting operation. Apart from this, under small size condition, 24 sweet peppers and under big size condition, 23 sweet peppers were harvested successfully. The thermo-col coating applied on inner sides of gripper helps to grasp the sweet peppers very smoothly and provide a box like structure around the sweet pepper so that the harvesting operation was performed without any physical damage to the fruit. The successful harvesting operation of sweet peppers under various conditions confirms the significant performance of the prototype. Also, the consistent working operation of prototype along with its performance validates the prototype based on simulation results. Table 3.6 represents the various features of the harvested sweet peppers in which the average values under each condition for big and small size sweet peppers were presented.

Table 3.6: Features of harvested sweet peppers

Feature / Condition	**Big size sweet pepper**				**Small size sweet pepper**			
	1	2	3	4	1	2	3	4
Average stem diameter, mm	6	5.7	6.1	5.2	3	3	4	3.8
Average stem cut height, mm	17	16	15	15	15	14	14	15
Average width of sweet pepper, mm	42	48	45	47	25	23	28	30
Average height of sweet pepper, mm	86	78	80	85	45	48	52	50

3.8 Conclusions

The gripping and cutting tool system was modeled and simulated in *Solidworks* successfully. The performance of the system was observed significantly reliable and effective. The static and fatigue studies of the system confirms the consistency and effectiveness with maximum factor of functionality. Thus, the physical characteristics and properties of the system were verified.

The gripping and cutting prototype was constructed and tested successfully based on the simulation results obtained from designed model. The experiments with 4 different conditions confirm the significant performance of the prototype. The 1st and 2nd conditions were observed having significant successful rate of harvesting than the 3rd and 4th conditions. In all 4 conditions, harvesting operation was performed successfully which helps to confirm that the proposed gripping and cutting tool system can be adopted for previous prototype of sweet pepper harvesting robot with same recognition system. As the situations which can cause the judgment errors during harvesting operation are not much common in advanced inclined supporting system in greenhouse, the possibilities of encountering judgment errors very often during harvesting operation are less. Moreover, the developed gripper and cutting tool system prototype for sweet pepper harvesting robot hand confirmed its successful performance. The static and fatigue characteristics results of simulated model were found similar during performance testing of prototype which confirmed the validity of designed model. Further, optimization of parameters with different materials, different gripping manipulation strategy and mechanism and improvement in the performance with various experimental conditions can be considered as the further research.

Chapter IV

PICKING SYSTEM - II

4. Picking System – II

This chapter is focused on increasing the shelf life of fruits and avoiding the viral transformation after harvesting of fruits which has impact of cutting process during harvesting operation. This chapter also explains the basic design and working principles of thermal cutting system along with prototyping of two types of thermal cutting system and their performance evaluation against harvesting operation. The postharvest inspection confirms the significant effectiveness of thermal cutting system to increase the shelf life of fruits and avoiding fungal and viral transformations.

4.1 Introduction

4.1.1 Background

The application of robots in agriculture is on increase in these days; especially, modern high-tech greenhouses are always equipped with automatic machines and control systems which are derived versions of numerically controlled machines. In greenhouse, every production system needs to obtain higher quality products at a lower cost in order to be competitive. By developing automatic systems that replace manpower in tasks when a person performs worse than an automatic device in terms of accuracy, repeatability and working cycle, the problem of higher quality products at a lower cost could be solved. Moreover, harvesting operation system has received a least amount of technological development for satisfactory automation. In agriculture, some damage resistant agricultural products like olives and almonds can be harvested using trunk or branch shakers [4.1]. However, delicate fruits, such as tomatoes, oranges, apples or strawberries for fresh market cannot be harvested using aggressive methods like shakers. If these methods were used, the fruits could be damaged by impacting the branches of tree during the fall or directly falling down on ground, and therefore fruit would loss the quality and results in reduction of trading cost in the fresh market. Also, there are probabilities of detaching unripened or small immature fruits by shaking the trunk or branches of tree [4.2]. Again, man power will be required to collect the fruits dropped on the ground after shaking resulting in increasing labor cost and cost of harvesting operation.

4.1.2 Problem Identification

The current method for collecting delicate fruits is hand harvesting. This method implies the use of temporal manpower which increases final cost of fruits in the market. Perhaps, adoption of robots in fruit harvesting is one of the important application in greenhouse horticulture that helps to save the labor cost, input harvesting energy consumption and to improve the resource utilization [4.3]. In application of robots for harvesting, robot grippers are main functional part of robot arm that helps to grasp the fruit and then cut accordingly. Thus, design of robotic grippers for efficient and delicate fruit harvesting has a vast research scope in robotic application for fruit harvesting. To avoid the physical damage to fruits, manual harvesting is preferred which significantly increases total cost of fruit production. On the other hand, the agricultural production rates are significantly influenced by utilization of robots and tools and techniques developed for decision support system [4.4]. Hence, for the efficient mechanical harvesting, the most important part is to design the proper gripper that can handle soft, delicate fruits, with respect to their various shapes and sizes [4.5].

On the other hand, as mentioned by *E. J. Van Henten et al.* [4.6] in horticultural practice, to avoid virus transformation, a knife used to cut the stem is repeatedly immersed in skimmed milk before each plant contact. For a robotic application this approach was not considered to be practical. Thus, for automated cutting of the stems, a thermal cutting technique provides better cutting approach by cutting the stem due to high voltage when come in contact with electrodes. During the contact of stem and electrodes, an electric arc is created which results in sudden temperature increase at that point and hence cutting operation is carried out. Evidently, high water content of the tissue material alleviates this process. This approach has two distinct advantages. First, during the cutting process viruses are killed due to the distinct temperature increase at the cutting surface. Second, the wounds of both the fruit and the plant are closed during the cutting process. This results in less water loss from fruit and consequently a longer shelf life. Also, by closing the wounds, the plant is considered to become less vulnerable to fungal diseases.

The Probabilities of virus transformation are higher during harvesting and post-harvesting processes which makes fruits vulnerable to diseases and reduces the shelf life of fruits. If farmers are aware of proper approaches for cutting, handling and storing fruits then vulnerability to fungal diseases can be reduced and quality of fruits will be improved.

4.1.3 Scope and Objectives of Research

To perform tasks of robotic fruit harvesting, a fruit must be detached from the plant during robotic harvesting with appropriate methods which is one of the key technical difficulties to be overcome. The detachment of fruits is accomplished usually by wrist motion of the robot or by certain cutting device. *Liu et al.* [4.7] demonstrated a spherical universal harvesting robotic picking system for tomatoes, apple and citrus. In the cutting system, a 30 W, 980 nm fiber-coupled semiconductor laser was used to cut the tomato peduncle. The cutting process was found significantly dependent on input laser power, defocusing distance, incident laser angle and diameter of peduncle. A 5 mm diameter peduncle needs almost 16 s to finish the cutting process and this cutting time further increases with increase in incident laser angle to peduncle. Furthermore, to accomplish cutting task, rotation of focusing lens was required since the laser beam focus diameter was smaller than peduncle diameter which made impossible to cut off the peduncle directly. The authors concluded that to improve the efficiency, setting negative defocusing distance and increasing laser beam focus diameter with increasing laser power.

According to *E. J. Van Henten et al.* [4.6], thermal cutting creates an important improvement versus the traditional knife based cutting; the application of thermal cutting for detaching process would be more effective to avoid viral and fungal transformations. So far, only few researchers [4.6-4.9] are engaged to develop efficient thermal cutting system which has received a least amount of technological development for satisfactory automation in past decades. Thus, by considering this fact, it was decided to develop an efficient thermal cutting system for sweet pepper harvesting robot. This may open a new passage for a virus free cutting system in harvesting robotics which helps to increase the shelf life of fruits after harvesting. The conceptual idea and model of thermal cutting system was designed and based on the concept, experimental prototypes were developed. The thermal knife (referred as TK) used by *E. J. Van Henten et al.* [4.6] for cucumber harvesting and the thermal cutting system (referred as TCS) developed for sweet pepper harvesting robot has following differences:

- Voltage: A high voltage range from 500 V to 700 V with high frequencies between 500 to 800 kHz were used in TK while TCS was designed to use low frequency and relatively lower voltage range than TK. The TCS uses voltage range from 210 V to 300 V at 50 Hz frequency and 20 mA current which was converted from 12 V DC power source.
- Power source: The power source used in TK was expensive Valleylab Solid State Electro surgery Model SSE3 while TCS designed to operate with 12 V DC power source and specially designed electric device. TCS needs less power input and consumes less energy when compared with TK.
- Current: The basic designs for TCS had two sub-designs; one was based on voltage and second was based on current. TK was designed based on only high voltage and high frequencies while TCS for sweet pepper harvesting robot presents two different types of system by using thermal cutting technique. The TCS design based on current uses 12 V DC power source; same as that of TCS design based on voltage.
- A new gripping system was designed which can fit with both designs of TCS. The grasping type of gripper driven by specially designed notch plate and a single servo motor used in gripping system. This design offers two types of electrode positioning for cutting operation while in cucumber harvesting robot, a suction type of gripper used with only one type of electrode positioning.
- The TCS was designed in such a way that both designs- based on voltage and based on current; should work with same gripper and basic components of TCS by changing only electrodes. This provides a benefit of easy and fast shifting between two designs in case of any fault or failure occurs in picking system. The safety fuse and switches were used to avoid any risk of dangerous accidents or any risk of injury to human if there would any unintentional contact between electrodes and human.

4.2 Design of Thermal Cutting System

4.2.1 System Design

The mechanical system to which this paper represents is a grasping and thermal cutting system which composed of two parts; the first part is aimed at grasping sweet peppers and the second part is aimed at cutting stem of sweet pepper from the plant by using thermal cutting technique. These both parts have been specifically designed with the purpose of imitating the manual operations by labors and preserving the nutritional values of fruit.

Figure 4.1 shows conceptual schematic of gripping and thermal cutting tool designed to harvest sweet peppers. In gripping part, two aluminum links were used as gripper to grasp fruits. To avoid physical damage to the fruit, 10 mm thermo-col coating was installed internally at gripper bars which make container structure. This structure helps to hold fruits without any physical damage and small fruits can be captured inside the container structure which avoids fruit falling down to ground. The gripper bars were driven by specially designed notch plate which measures 60 mm X 80 mm in dimensions and driven by servo motor. The servo motor was installed on supporting frame and the rotary power was transferred to the notch plate by means of rack and pinion mechanism. Two wooden poles were used to connect notch plate and gripper bars. One end of poles was fixed with gripper bars while another end kept free which help to move the wooden poles smoothly through the curvatures on notch plate. When notch plate moves forward, gripper bars moves inward resulting in grasping the fruits and cutting the stem of fruit while when notch plate moves backward, gripper bars moves outward leading to release the harvested fruit. The forward and backward movements of notch plate were controlled by servo motor controller and control program. In thermal cutting part, two electrodes were installed at the front end of notch plate and an electric input was supplied to electrodes. The cutting system was designed to operate with 12 V DC power source and to obtain high voltage for cutting operation, a small electric device was designed and fabricated. This small electric device works as an inverter and help to amplify the output voltage. In between this device and electrode, a small safety fuse and switches were used as safety precautions.

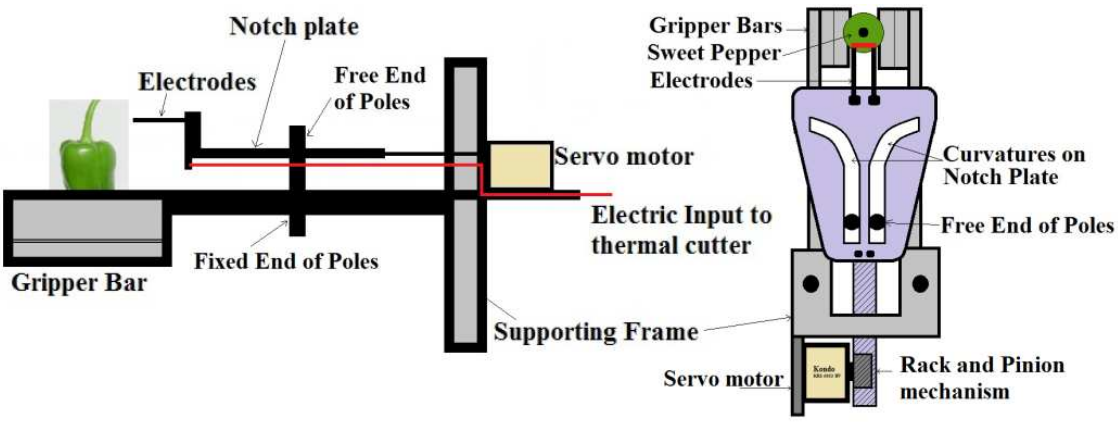


Figure 4.1: Conceptual schematic of thermal cutting system

4.2.2 System Operating Mechanism

The important part in the system operating mechanism was to transfer the rotary motion of the servo motor to notch plate by efficient mechanism as the place and workspace for movement was very small. To solve this, the servo motor was installed at the end of supporting frame and rotary motion from servo motor was transferred to linear motion by means of rack and pinion mechanism. The components for this rack and pinion mechanism were modifies in the laboratory from various materials. The transferred linear motion of servo motor drives notch plate and during the forward and backward movement of notch plate, the poles engaged in the curvatures and fixed with gripper bars drives gripper bars accordingly. The curvature notches on the plate were designed such that when plate moves forward, gripper bars moves inwards to grasp the fruit and when plate moves backwards, gripper bars moves outwards to release the fruit. This combined movement of system allows grasping the fruit and cutting fruit stem simultaneously. The servo motor *Kondo KRS 6003 HV* [4.10] was controlled through computer and control program was developed in Visual Basic C++. The vertical distance between gripper bars and notch plate that drives the electrodes for cutting operation was maintained by considering physical characteristics and properties of sweet peppers. This vertical distance also helps to cut the stem of fruit at appropriate length and work as pre-set fruit stem cutting mechanism. This vertical distance can be adjusted according to the situations or requirements by adjusting the height of screw that connects rack and pinion mechanism and notch plate.

4.2.3 Speed Control of System

Figure 4.2 represents detailed block diagram of control system used to operate and control gripping and cutting system in which program was written in Visual Basic C++ to interface between servo motor and computer. The servo controller *KCB-1* [4.11] was used to control the Kondo servo motor. The motor rotates by 270^0 without restriction and program was developed to drive the motor by 160^0 angle from home position, wait for 3 seconds at final position and then drive back to home position. This allocation allows to move the gripper inward and grasp the fruit while moves the electrodes forward and start cutting process which may depends on the diameter of each fruit stem. The waiting time of 3 seconds was allowed to accomplish and confirm the cutting process; if the cutting process was still not finished then this waiting time would help to finish the process.

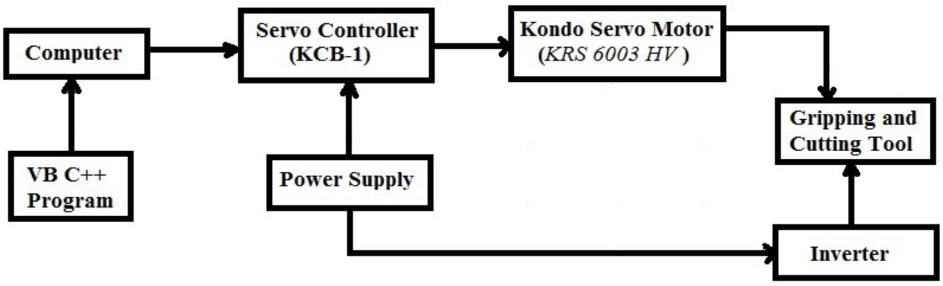


Figure 4.2: Block diagram of speed control of system

In the block diagram of speed control of system, the power was provided to the servo controller and to inverter. Under thermal cutting system, two different prototypes were designed and fabricated based on current and temperature. When thermal cutting system based on voltage was in operation; a special electric device designed to amplify the voltage and works similar to inverter, the power was supplied to inverter. But when thermal cutting system based in current was in operation; this system do not need any current amplification and hence the power was supplied to servo controller only and inverter was omitted from the system. The amount of input power was considerably selected based on the several trial and error studies on voltage and current requirement for cutting operation and power consumption during the cutting operation. This makes the thermal cutting system different than other picking system of harvesting robot.

4.3 Thermal Cutting System

The prototype of thermal cutting system was designed and built by using aluminum, plywood and plastic material. Aluminum was used for the construction of supporting plates, gripper bars; plywood was used for poles and connecting links between gripper bars and poles while notch plate was fabricated by using plastic material. The model of thermal cutting system designed in the solidworks can be seen in Figure 4.3. When installing this prototype on harvesting robot manipulator as an end-effector, operator needs to connect notch plate to servo motor shaft and fix the supporting base plate on robot arm.

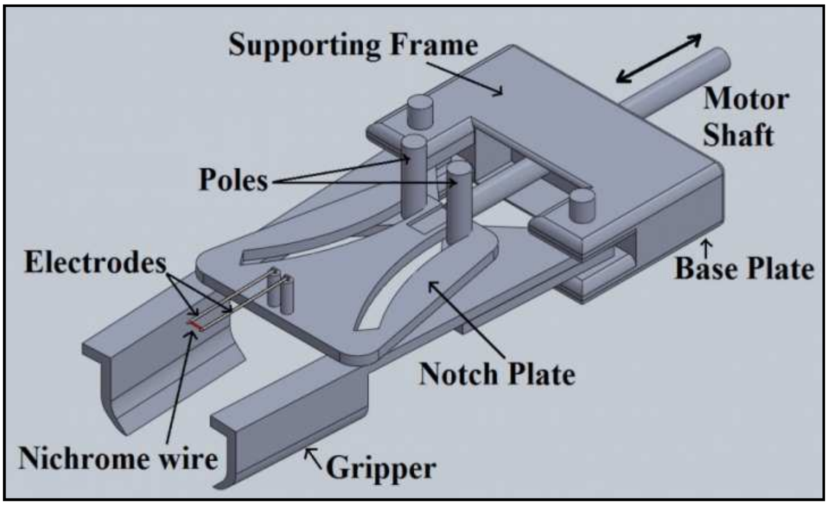


Figure 4.3: System model design of thermal cutting prototype

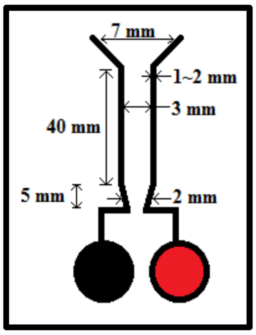
In the experimental prototype, two different types of systems were built depending on the voltage and current potentials viz., Electric arc thermal cutting system and Temperature arc thermal cutting system respectively. An electrodes installed at the front side of notch plate can be replaced accordingly system requirements. For switching electric arc system to temperature arc system or vice-versa, an operator only needs to replace the electrodes and electrical input to the system. In the electric arc system, two iron metal rods varying from 1 mm to 2 mm diameter size were used while in case of temperature arc system, two steel rods were connected by using nichrome wire. The temperature arc system was dependent on nichrome wire temperature response to current and as corrosion factor of steel is less than iron, the steel rods can be used for longer time compared with iron rods. In case of electric arc system, the system depends on voltage which needs a good conductor of electricity with high electricity conductivity and less resistivity. As an alternative for nichrome wire in temperature arc system, tungsten wires also tested for temperature response to input current but nichrome wire found more suitable than tungsten wire.

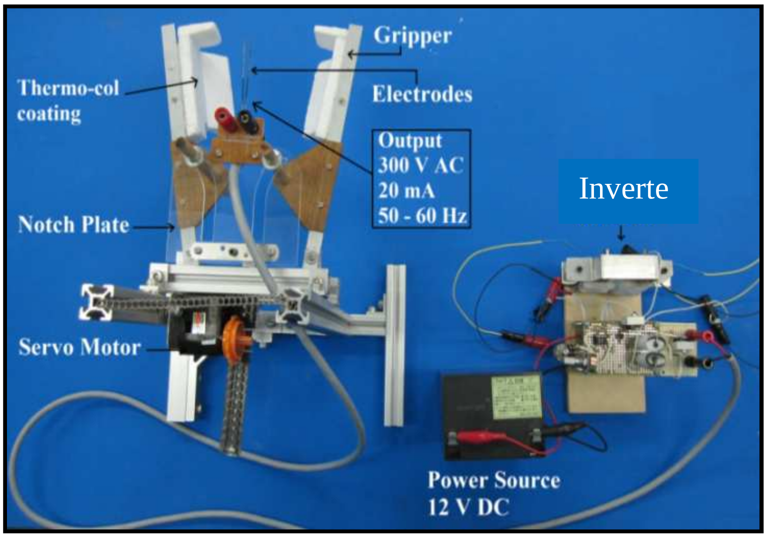
4.3.1 Electric Arc Thermal Cutting System

The design of Electric Arc Thermal Cutting System (EATCS) was based on the input potential of voltage. As described in system design concept, a servo motor was installed at the end of the supporting frame and rotary motion of servo motor was transferred to linear motion by using rack and pinion mechanism. The transmitted linear motion was provided to the notch plate and poles were used to connect notch plate and gripper bars. One end of poles was fixed with gripper bars while another ends kept free to move smoothly inside the curvatures on the notch plate. The forward - backward movement of the notch plate results into opening - closing of the gripper bars and detachment of fruit stem at the same time. 10 mm thick layer of thermo-col was installed inside the gripper bars to avoid any physical damage to fruits when grasping action takes place.

For electric input, as cutting operation intended to take place by high voltage, direct voltage input was not possible from the batteries or using electricity source. To solve this problem, a special electric device was designed which works similar to an inverter. The device was capable of changing 12 V DC battery input to output of 300 V AC with 50-60 Hz frequency at 20 mA current. In the experimental prototype, input from 12 V DC battery source was supplied to this device and output from this device was extended to the electrodes. Two electrodes were installed at the front end of notch plate as shown in the Figure 4.4 (b). Two types of electrode set varying in diameter size; 1 mm and 2 mm were selected for experiments and distance between two electrodes was set as shown in Figure 4.4 (a).

A safety fuse and switches were used to avoid any dangerous accidents or any risk of injury to human and the inverter device was placed away from the system to allow safe operation during harvesting process.





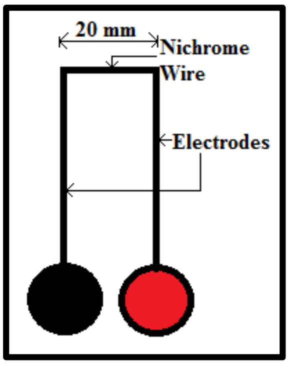
(a) Electrode positioning (b) EATCS Prototype

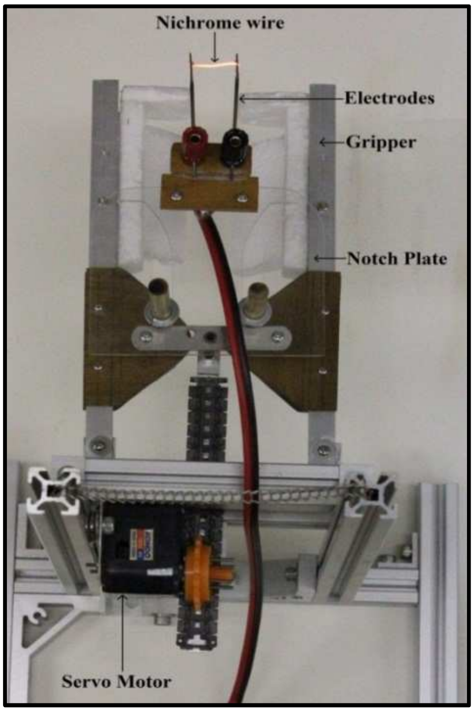
Figure 4.4: Electric arc thermal cutting system prototype

4.3.2 Temperature Arc Thermal Cutting System

The design of prototype of temperature arc thermal cutting system (TATCS) was based on current input in which cutting operation intended to take place with the help of high temperature. The working mechanism and all components of TATCS were same as that of EATCS expect electrode positioning. In TATCS, two front electrodes were replaced from main system prototype by another two electrodes placing 20 mm apart from each other. These two electrodes were connected by Nichrome wire. The system prototype for TATCS can be seen in Figure 4.5 along with electrode positioning. The material used for two electrodes were steel as the corrosion factor of steel is less than iron which helps to deliver a good response to increase in temperature with respect to increase in input current.

The input current was supplied and controlled according to the manufactures recommendations of nichrome wire for current carrying capacity and resistance. When the current applied to both ends of nichrome wire, the wire gets heated and turn into high temperature arc. An increase or decrease in the temperature of nichrome wire depends on the input current supplied. On the other hand, servo motor keeps working according to the program which helps to move notch plate resulting in grasping and cutting operations of fruit.





(a) Electrode positioning (b) EATCS Prototype

Figure 4.5: Electric arc thermal cutting system prototype

4.4 Experiments of Thermal Cutting System

4.4.1 EATCS Experiments

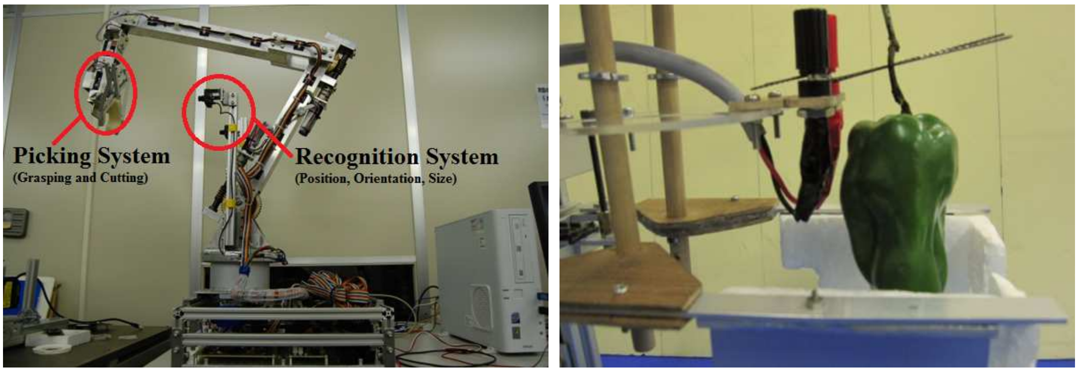
The application of high voltage with 50 Hz frequency for cutting operation was tested as a part of thermal cutting system. The experimental set up of EATCS includes DC power source, an electric device similar to inverter, gripping system and thermal cutting system. The electric device similar to inverter was placed away to avoid any interruption during the experiments.

When cameras capture the images and image processing software detects the sweet peppers to be harvested, 12 V DC input was supplied to the device which produces 300 V AC with 50 Hz frequency at 20 mA current as output. At the same time servo motor starts to operate according to the control program. The transmitted linear motion from servo motor drives the notch plate and gripper bars together. The electrodes on notch plate moves in forward direction and gripper bars moves in inward direction. When the stem of fruit came in contact with electrodes, due to the high voltage which forms electric arc between two electrodes causes vaporization of water from fruit stem and results in detachment of each cell particle of fruit stem and hence cutting operation takes place. On an average, the stem of matured sweet pepper measures 5 mm. In the positioning of the electrodes, the entrance was kept 7 mm which helps to position the fruit stem inside two electrodes. Further, as the notch plate keep moving forward, the span of 40 mm at 3 mm distance apart from each other allows deeper cut in the fruit stem and finally the exit span 5 mm at 2 mm distance apart from each other finishes the cutting process. The majority of cutting operation accomplished over 45 mm distance span that is between entrance and middle span of electrodes. Simultaneously, gripper bars also keep moving inward with forward movement of notch plate which allows grasping of sweet pepper at the same time of cutting.

In the EATCS, the diameter of electrodes and output voltage were important parts of the system which affects cutting time and cutting rate. By keeping these points in view, the system was tested by varying diameter of electrodes and output voltage from inverter. The diameter of electrodes was varied in two steps, 1 mm and 2 mm while the output voltage was varied from 150 V to 300 V in steps of 10 V. For efficient cutting operation by using iron electrodes and high voltage, small grooves were made on the electrodes so that when electrodes moves forward, the small notches on the electrodes help to cut the fruit stem efficiently. The grooves on the electors also help as irregularity on the surface area of electrodes which increases the friction between two surfaces. The variation of the output voltage was controlled with the help of variable resister of inverter.

The speed of servo motor that moves the notch plate and electrodes was also considered as affecting parameter but the relationship between cutting time and speed of servo motor was not found effective to output voltage and diameter of electrodes and hence speed of servo motor was kept constant throughout the experiments. Figure 4.6

shows EATCS prototype during the harvesting experiments with 300 V output voltage and 1 mm electrode diameter.



(a) Harvesting Robot Prototype (b) EATCS Prototype

Figure 4.6: Testing of EATCS prototype

4.4.2 TATCS Experiments

The experimental set up of TATCS includes DC/ AC power source and gripping system attached with thermal cutting system. As mentioned in the design of TATCS, the two electrodes were placed 20 mm away from each other and connected with nichrome wire. The temperature generated at nichrome wire depends on current supplied to the nichrome wire. The rest of working principle and control system of TATCS was similar to that of EATCS. In TATCS, inverter was not used as this system does not need any current amplification to perform the cutting operation.

In the TATCS, generation of temperature was the important factor in cutting process of fruit stem which had influence of nichrome wire diameter. Hence, by considering this factor, prototype was tested by varying diameter of nichrome wire and input current to the nichrome wire. 0.02 mm, 0.5 mm and 1 mm diameters were selected for the experiments and tested these nichrome wire diameters by adopting them for fruit stem cutting operation. The input current was varied from 0.5 A to 12 A in steps of 0.5 A and temperature was measured at the middle section of the nichrome wire with the help of infrared thermometer. Figure 4.7 shows the TATCS prototype during the harvesting experiments with 8 A output current and 0.5 mm diameter nichrome wire. In TATCS also, the speed of servo motor kept constant throughout the experiments as the relationship between cutting time and speed of servo motor was not found effective with generation of temperature and variation in diameter of nichrome wires.

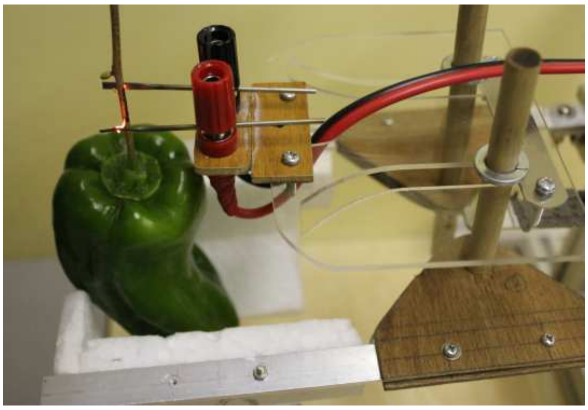


Figure 4.7: Testing of TATCS prototype

In both EATCS and TATCS prototype experiments, as the size of fruit stem also influences the cutting time and cutting rate, hence the fruit stem size was varied from 1 mm to 5 mm in steps of 1 mm increase in the stem diameter size. An average 5 mm stem size is common in the matured sweet peppers of 2L category in which diameter of sweet pepper measure 48 mm and height measures 82 mm. Table 4.1 summarizes the parameters varied under each thermal cutting system to evaluate the performance.

Table 4.1: Parameters varied during experiments

Parameters	**Electric Arc** (Electrode diameter)	**Temperature Arc** (Nichrome wire diameter)
Diameter	1, 2 mm	0.02, 0.5, 1 mm
Input	150 to 300 V	0.5 to 12 A
Increase in resistance, %	-	Depends on temperature
Fruit stem size, mm	1 to 5 mm	
Cutting time, s	Depends on above parameters	
Quality of harvested fruits	Preservation days at normal room temperature and ambient pressure	

4.5 Results and Discussion

During the testing of prototype, all sweet pepper samples were harvested successfully without any difficulties by using both thermal cutting systems. Both thermal cutting systems, EATCS and TATCS had significant influence on rate of cutting stem and time required to accomplish the cutting process. During the harvesting process, due to the thick 10 mm thermo-col internal layer on the gripper bars, none of the harvested sweet peppers were damaged physically. The thermo-col layer was found very efficient to grasp the fruits without any damage.

4.5.1 EATCS Results

The EATCS prototype was tested with 1 mm and 2 mm diameter electrodes to observe the effect of electrode diameter and output voltage from inverter. 1 mm diameter electrodes were found significantly suitable for harvesting process compared with 2 mm diameter electrodes. The time taken by 1 mm and 2 mm diameter electrodes to finish the cutting process was found 2.2 seconds and 5 seconds respectively at 300 V output for 5 mm diameter fruit stem. Figure 4.8 shows the completion of the harvesting operation task while inset shows the harvested sweet pepper (45 mm in diameter, 72 mm in height, 5 mm stem diameter and 4 mm height of cut).

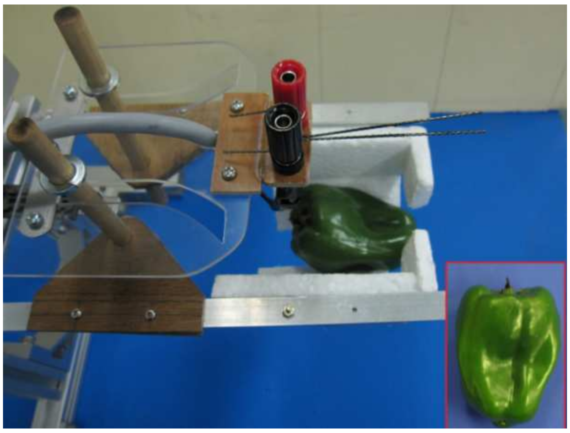


Figure 4.8: Harvested sweet pepper

As the output voltage from inverter and time required to cut the fruit stem was considered important factor that may affects performance of the EATCS system; these two parameters were tested to find out the relationship between them and how they relate with cutting operation. The graph in the Figure 4.9 represents the relationship between output voltage from inverter and time taken by the EATCS for cutting the stem of fruit when output from device was varied from 150 V to 300 V in steps of 10 V.

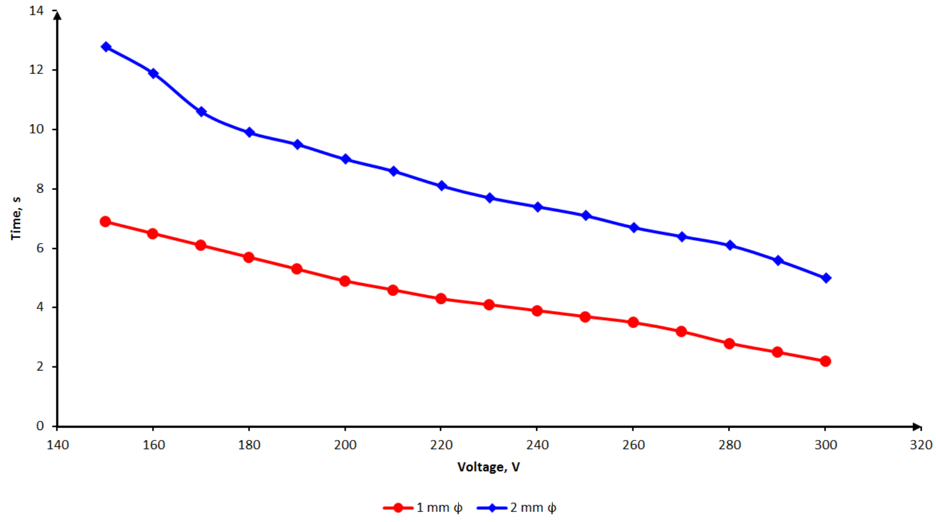


Figure 4.9: Relation between output voltage and time to finish the cutting of stem

The time required to cut the fruit stem was decreased with increase in voltage and at every increased step of voltage, time taken by 1 mm diameter electrodes were found lesser than 2 mm diameter electrodes. This difference was found due to increase in the diameter of electrode which decreases the resistance of electrodes and hence more power required to carry the voltage. At this point, the discharge required to perform the work done at low current was not enough and hence 2 mm electrodes took extra time than 1 mm electrodes. 1 mm diameter electrodes required 7 seconds at 150 V and 2.2 seconds at 300 V while 2 mm diameter electrodes required 12.8 seconds at 150 V and 5 seconds at 300 V to finish the cutting operation of fruit stem.

4.5.2 TATCS Results

The TATCS prototype was tested with 0.02 mm, 0.5 mm and 1 mm diameter nichrome wire to observe the effect of wire diameter on stem cutting rate and cutting time. The 12 V DC input current supplied to nichrome wire, varied from 0.5 A to 12 A in step of 0.5 A; temperatures were recorded at each steps. Figure 4.10 shows the nichrome wire temperature response to increase in input current.

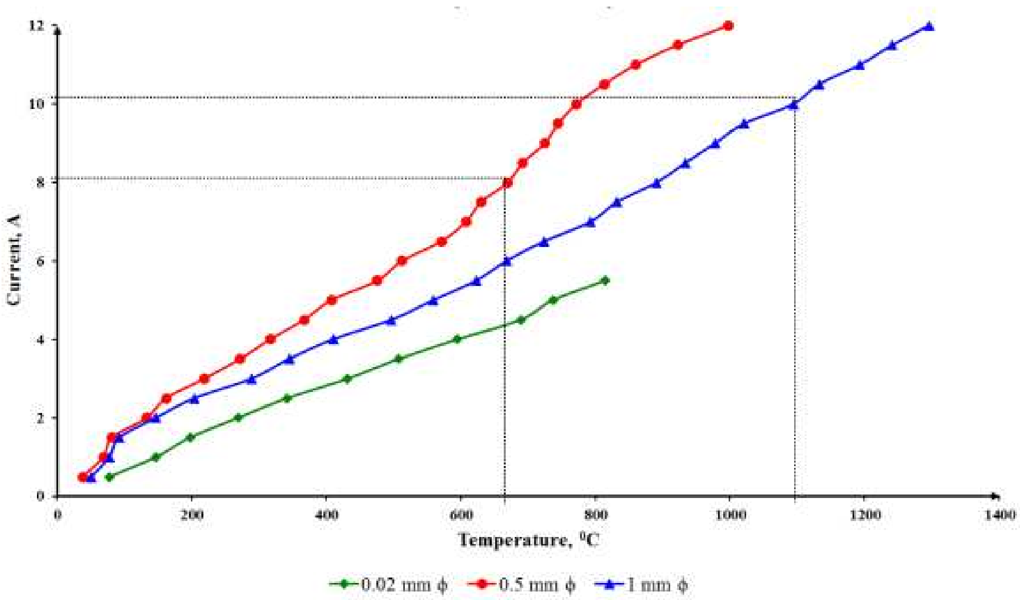


Figure 4.10: Nichrome wire temperature response

During experiments, it was found that 0.02 mm diameter Nichrome wire starts to melt beyond 5 A current and hardly could reach to 815^0 C temperature at which cutting the fruit stem was not possible due to softening and flexibility of wire. 0.5 mm diameter nichrome wire start to heat up rapidly beyond 2 A current and reach up to 1000^0 C and at this temperature, the wire was found hard enough and steady to cut the fruit stem. For both 0.02 mm and 0.5 mm wires, 12 V DC power source was enough to generate high temperatures but in case of 1 mm diameter wire, due to increase in cross-sectional area of wire and contact area between wire surface and fruit stem; wire required additional power source to generate high temperature. Thus, amplifier with AC power supply was used for 1 mm diameter wire to observe temperature response. At the beginning, wire consumes some power to heat up and then temperature starts to increase rapidly. At 12 A current, the temperature was recorded 1296^0 C and there was no effect of softening or flexibility of wire. Throughout the response observation experiments, 0.5 mm diameter nichrome wire had higher temperature response at every increased step of current compared with 1 diameter mm nichrome wire diameter. The only difference was found that 1 mm diameter nichrome wire attended higher temperatures than 0.5 mm diameter wire when 0.5 mm diameter nichrome wire reached to maximum temperature generation point and could not generate higher temperature than that point.

The softening of the nichrome wire at high temperatures also had effect on stem cutting process and due to this reason, the relationship between percent increase in the resistance of wire and corresponding temperatures was investigated which helps to decide the optimum current input range to obtain high temperatures. For this case, 0.02 mm diameter nichrome wire was omitted as it melts beyond 5 A current. Figure 4.11 represent the relationship between percent increase in the resistance of wire and temperatures for 0.5 and 1 mm diameter nichrome wire.

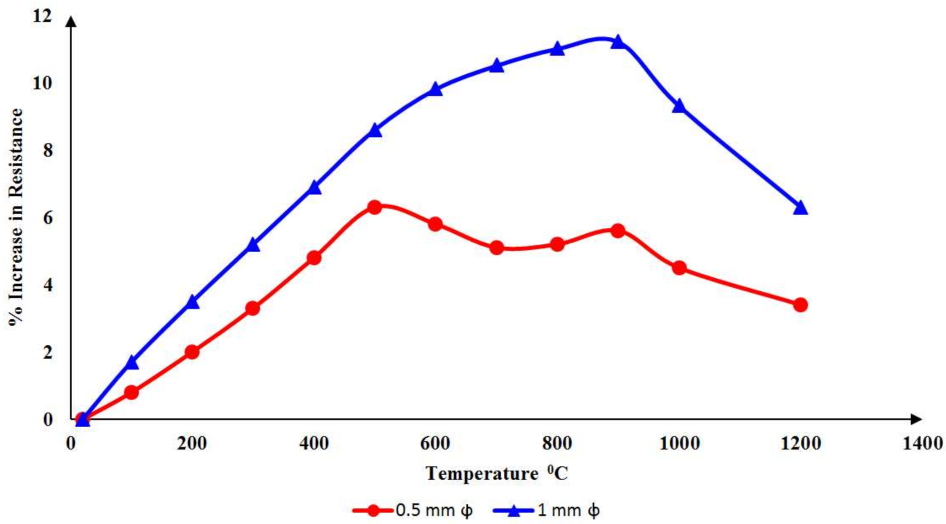


Figure 4.11: Effect of temperature on resistance of nichrome wire

In case of 0.5 mm diameter nichrome wire, the resistance starts to increase with increase in temperature and approximately at 500^0 C start to fall down and again start to rise at 700^0 C and then after 900^0 C continue to decrease. The temperature range of 700^0 to 900^0 C had sudden growth in the percentage increase in resistance and this range was yield by 8 A to 10 A current. This sudden increase in resistance was found as an important characteristic of 0.5 mm diameter nichrome wire which could be adopted as optimum temperature range for cutting process. This adoption also has one advantage; when fruit stem touches the hot wire, temperature of that spot suddenly drops to some extent and if the wire is at softening condition then wire breaks into pieces. Hence, at this stage, if the resistance suddenly increases then it helps to harden the wire and ceases breaking of wire. In case of 1 mm diameter nichrome wire, the resistance of wire increased with increase in temperature and after 900^0 C resistance start to decrease with increase in temperature. Though the resistance starts to decrease after 900^0 C, the percentage value of decrease in resistance was found higher than 0.5 mm diameter nichrome wire which implies that the hardness of 1 mm diameter wire was higher than 0.5 mm diameter nichrome wire at same temperatures.

On the other hand, as the fruit stem varies per fruit and cutting the fruit stem of variable stem size had influence of cutting rate and cutting time of temperature arc thermal cutting systems, hence nichrome wires were also tested for cutting operation under variable fruit stem size varying from 1 mm to 5 mm. In case of 0.02 mm diameter wire, before 5 A current, when wire touches the fruit stem, temperature drop was occurred up to certain extent and when input current increased to increase the temperature, wire starts to melt beyond 5 A current and finally break into pieces. At this point, it was concluded that the 0.02 mm diameter wire failed to cut the fruit stem larger than 2 mm in diameter size and cannot be used for cutting average size sweet pepper fruit stem. 0.5 mm and 1 mm diameter wires were found significantly efficient for cutting an average size fruit stem. Further, 0.5 mm diameter wire was able to cut the fruit stem of 8 mm in diameter while 1 mm diameter wire was able to cut the fruit stem of 12 mm in diameter. The only difference found that the 0.5 mm diameter wire was operated by 12 V DC power supply whereas 1 mm diameter wire was operated by 100 V amplifier connected to AC power source. This indicates that though 1 mm diameter nichrome wire produces high temperature range but it required additional power source to perform stem cutting operation which results in use of excessive power while 0.5 mm diameter nichrome wire produces lesser temperature range than 1 mm diameter nichrome wire but operated with low power source and accomplished the fruit stem cutting task. This implies that the fruit stem cutting operation could be done by adopting 0.5 mm diameter nichrome wire at less power input which can generate higher temperature range useful for variable fruit stem cutting operation.

Table 4.2 illustrates time taken by each thermal cutting system to cut the fruit stem of various sizes. In thermal cutting systems, 20 samples were tested under EATCS and TATCS, each electrodes and nichrome wire diameters and average time taken in each case to accomplish the harvesting operation was computed.

Table 4.2: Time taken by thermal cutting systems for harvesting

	Electric Arc (Electrode diameter)		**Temperature Arc** (Nichrome wire diameter)		
Fruit stem diameter	ϕ 1 mm	ϕ 2 mm	ϕ 0.02 mm	ϕ 0.5 mm	ϕ 1 mm
1 mm	1.2 s	2.7 s	6 s	1.1 s	0.92 s
2 mm	1.6 s	3.5 s	8 s	1.1 s	0.99 s
3 mm	1.9 s	4.1 s	-	1.3 s	1.1 s
4 mm	2.1 s	4.7 s	-	1.4 s	1.3 s
5 mm	2.2 s	5 s	-	1.5 s	1.4 s

From above table, it was clear that in EATCS prototype, 1 mm diameter was found more effective for cutting fruit stem of average 5 mm diameter size in 2.2 seconds as compared with 2 mm electrode which required 5 seconds. In case of TATCS, 0.5 and 1 mm diameter nichrome wires were found significantly efficient but 1 mm diameter nichrome wire needs additional power than 0.5 mm diameter nichrome wire to cut the same size fruit stem. Also, the cutting time difference between these two wires found 0.1 second which was negligible and could be accepted for harvesting operations in greenhouse. Hence, 0.5 mm diameter wire for cutting process at lower power input and higher temperatures could be considered as recommendation. Among the EATCS and TATCS prototypes, TATCS prototype was found significantly efficient as it accomplished the cutting fruit stem task in 1.4 seconds compared with EATCS prototype which required 2.2 seconds to cut the fruit stem of an average 5 mm diameter size. In TATCS, the 0.5 mm diameter nichrome wire required small input power source and finishes the task in lesser time than EATCS, 1 mm diameter electrodes which not only took more time to cut the fruit stem but also required amplification of voltage.

To validate the obtained results, a theoretical analysis was carried out to check the feasibility of thermal cutting prototypes. For that purpose, following equations were considered:

$$r_{0.02} < r_{0.5} < r_1 \quad (4.1)$$

$$A_{0.02} < A_{0.5} < A_1 \quad (4.2)$$

$$R_{0.02} > R_{0.5} > R_1 \tag{4.3}$$

$$P_{0.02} < P_{0.5} < P_1 \tag{4.4}$$

where subscripts represent nichrome wire diameter in *mm* and;

$r_{0.02}$, $r_{0.5}$ and r_1 = Radius of nichrome wire, *m*

$A_{0.02}$, $A_{0.5}$ and A_1 = Cross-sectional area, mm^2

$R_{0.02}$, $R_{0.5}$ and R_1 = Resistance, *Ω*

$P_{0.02}$, $P_{0.5}$ and P_1 = Power, *W*

The above Equations 4.1 – 4.4 were derived from following equations:

$$Area\ of\ wire, A = \pi r^2 \tag{4.5}$$

$$Resistance\ of\ wire, R = \rho L/A \tag{4.6}$$

$$Power, P = VI = I^2R = V^2/R \tag{4.7}$$

where,

ρ = Resistivity of nichrome wire = 1.5×10^{-6} *Ωm*

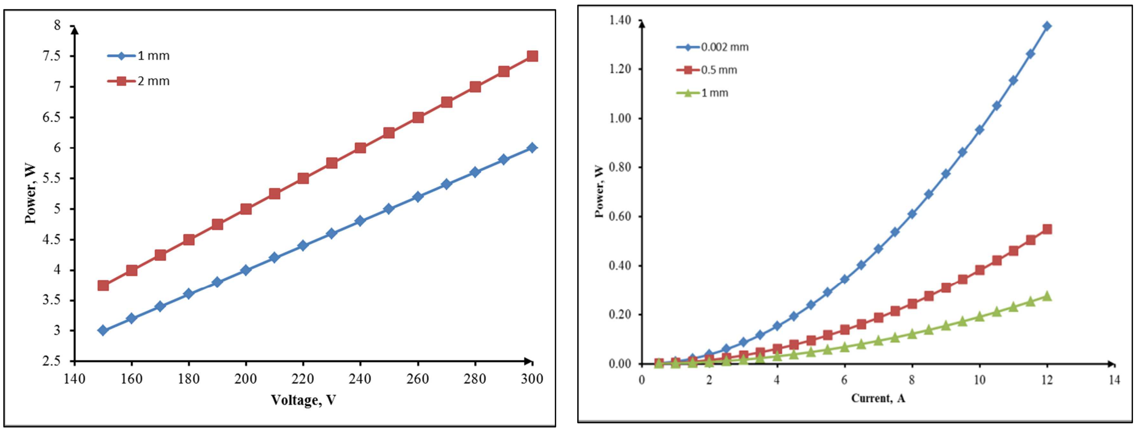
L = Length of wire, *m*

I = Current flowing through wire, *A*

V = Voltage across nichrome wire, *V*

From above equations, it was clear that when radius increases, cross-sectional area increases; resistance decreases and power increases. This means the radius of nichrome wire is directly proportional to area, area is inversely proportional to resistance and resistance is inversely proportional to power, the derived equations can be applied to investigate the radius to power relationship. Figure 4.12 shows the power charts for EATCS and TATCS respectively in which it was observed that increase or decrease in diameter had significant effect on power consumption by electrodes and nichrome wires.

In case of EATCS, power consumption was increased with increase in the diameter of electrodes. The increment in diameter of electrodes increases cross-sectional area reducing the resistance of electrodes which further increases the power requirement. It was found that the radius and power requirement by electrodes follows the trend derived in the Equations 4.1 - 4.4. On the other hand, in case of TATCS, the power requirement trend was found completely reverse as that of theoretical analysis and equations obtained. The power consumption was reduced with increase in diameter of nichrome wire. The main reasons for these opposite trend were very small amount of resistance of nichrome wire over power source resistance. The internal resistance of power source was higher than the load resistance and according to the maximum power transfer theorem; if the load resistance is smaller than the source resistance, then most of the power ends up being dissipated in the source, and although the total power dissipated is higher, due to a lower total resistance, it turns out that the amount dissipated in the load is reduced. In other words, the small amount of nichrome wire resistance and high internal resistance of battery caused the power dissipation in the source. This affected the reduction in output power when radius of wire increased.



(a) EATCS prototype (b) TATCS prototype

Figure 4.12: Physical configuration effect on power consumption during stem cutting

Based on the analysis mentioned above, the comparison of EATCS and TATCS for optimal parameters recommended to obtain the significant results can be seen in Table 4.3. The parameters mentioned in the table below helps to decide the best physical configuration combination to obtain the good results.

Table 5.3: Optimal parameters for thermal cutting system prototypes

Parameters	**EATCS**	**TATCS**
Diameter, mm	1	0.5
Length, mm	50	20
Voltage, V	300	12
Current, A	0.02	8 ~ 10
Temperature, ^{0}C	~ 30	670 ~ 1150
Cutting time, s	2.2	1.5
Physical damage to fruit	No	No
Preservation period	9 ~ 15 days from harvesting day	

If power saving factor is taken into consideration, then TATCS prototype with 0.5 mm diameter nichrome wire provides better results by using less power source input, generating high temperature range and accomplishing fruit stem cutting task in less time compared with other prototypes. The EATCS prototype can be adopted for single fruits or fruits without any occlusion as the two electrodes required moving in forward direction to finish the cut on stem and if any occlusion occurs, it might create obstacle to the cutting system. TATCS prototype can be used in any conditions as the front end of the cutting systems moves straight and even if any occlusion of fruits occurred, it does not affect the nichrome wire.

4.6 Quality of Harvested Sweet Peppers

The effect of quality change due to thermal cutting system was observed on harvested sweet peppers. This post-harvesting investigation helps to determine the shelf life period of the harvested perishable sweet peppers and also to decide whether thermal cutting system was effective to avoid any viral and fungal transformation during harvesting operation. The harvested sweet peppers were grouped under EATCS, TATCS and normal scissors cutting categories. The samples were kept in common place at room temperature and ambient pressure and sample sides were rotated once a day by safe and clean gloves. The samples were checked every day for any physical change occurrence on the outer skin.

It was observed that the samples cut by thermal cutting systems showed minor physical changes like wrinkle formation after day 9 while the samples cut by normal scissors starts to show major physical changes after day 5 such as turning the outer green skin to brown-red, wrinkle formation on skin and becoming softer when touched. On day 15, samples cut by scissor was found almost spoiled while samples cut by thermal cutting showed only minor physical changes like formation of wrinkles and becoming softer. This concludes that the samples cut by thermal cutting systems were more likely to preserve the quality of fruits due to less virus transformation which makes them less venerable to fungal diseases. In the Figure 4.13; sample 1 and 2 were cut by EATCS, sample 3 by scissor and sample 4 by TATCS. The brown-red spots on sample 3 were easily detectable by eyes and considered as not good for use after day 9 while other samples can still be used.

Figure 4.13: Post-harvest inspection of sweet peppers

The post-harvest inspection of harvested sweet peppers confirms that the thermal cutting systems were significantly effective and efficient to preserve the quality and shelf life of harvested sweet peppers. The thermal cutting system terminates the viral and fungal activity by closing and covering the stem parts of fruit by burning action. This sealed portion of fruit stem ceases the path which was accessible by viruses and due to this fruits became less vulnerable to fungal activities which help to preserve the shelf life and quality of perishable sweet peppers.

4.7 Conclusions

The thermal cutting system prototypes were designed, developed successfully and tested for performance. In thermal cutting, EATCS and TATCS prototypes were developed based on voltage and current potentials respectively. In case of EATCS, 1 mm diameter electrodes were found efficient for cutting operation compared with 2 mm diameter electrodes. In case of TATCS, 0.5 mm and 1 mm diameter nichrome wires were found significant but 1 mm diameter nichrome wire needs additional power to operate while 0.5 mm diameter nichrome wire works efficiently with 12 V DC power source. Increase in the diameter of wire needs additional input power which results in excessive energy consumption. A sudden increase in the percentage of increase in resistance of 0.5 mm nichrome wire assist to stabilize the hardness of wire at higher temperatures and this characteristic found advantageous for cutting operation. As the cutting time difference between 0.5 mm and 1 mm diameter nichrome wires was found negligible which can be accepted for harvesting operations in greenhouse and 0.5 mm diameter nichrome wire works significantly and effectively by cutting up to 8 mm fruit stem diameter; 0.5 mm diameter nichrome wire was recommended for TATCS. Among the EATCS and TATCS prototypes, TATCS prototype was found significantly efficient as it accomplished the cutting fruit stem task in 1.4 seconds compared with EATCS prototype which required 2.2 seconds to cut the fruit stem of an average 5 mm diameter size. In TATCS, the 0.5 mm diameter nichrome wire was recommended which required small input power source and finishes the task in lesser time than EATCS, 1 mm diameter electrodes which not only need more time to cut the fruit stem but also required amplification of voltage. The performance testing of thermal cutting system prototypes confirms that TATCS delivered significantly efficient and effective performance than EATCS by accomplishing the harvesting operation in lesser time and at small power input. The TATCS prototype with 0.5 mm diameter nichrome wire can be used as best suited for harvesting of sweet peppers which not only uses low power but also finishes the task quickly. The thermo-col coating around gripper bars causes no physical damage to the fruits and container structure grasps the fruits in good condition.

In case of fruits harvested by using thermal cutting system, the quality of fruit can be preserved up to 15 days with less or almost no virus transformation while in case of fruits harvested by normal scissors, the fruits start to show changes in physical appearance at day 5 and after day 9 fruits were found unusable. This concludes that the thermal cut seals the stem cut parts which helps to cease fungal or bacterial transformation and helps to increase the shelf life and quality of the harvested fruits. Thus, thermal cutting method could be adopted for harvesting of other fruits and vegetables too which may help to reduce the viral and bacterial activities and can be preserved for longer time when compared with normal cutting methods.

The proposed thermal cutting system is compact, easy to replace the electrodes, simple in operation and use, provides advantages of preventing viral and bacterial transformation and increasing shelf life and quality of perishable fruits. Moreover, for EATCS, adoption of electrodes with diameter smaller than 1 mm, stabilizing the output from inverter with higher frequencies, changing material of wire for TATCS and quality testing for harvested fruits by chemical methods could be considered as further research.

Chapter V

RECOGNITION SYSTEM: I

5. RECOGNITION SYSTEM – I

This chapter illustrates the recognition system used in the sweet pepper harvesting robot. The recognition system described in this chapter was based on color imaging processing which help to locate the fruits on trees and provide the 3D coordinates of recognized fruits. This positional information was useful during manipulator movement to the target fruits. This chapter explains the components of sensing system, steps involved in recognition system and how to locate and determine the position and orientation of detected fruits on tress.

5.1 Introduction

5.1.1 Background

For last several years, computers have been used extensively for analyzing the images and obtaining the data from images. But, due to variability of the agricultural objects, it is very difficult to adopt the existing industrial algorithms to the agricultural domain. To cope with this variability, the methods for agricultural domain knowledge in algorithms need to be studied which could support the variations and flexibility in agricultural objects. There are many processes available in agriculture where decisions are made based on the appearance of the product [5.1]. The techniques used for these applications are mostly successful under the constrained conditions for which they were designed, but the algorithms are not directly usable in other applications. In principle, computers are flexible because they can be re-programmed, but in practice it is difficult to modify the machine vision algorithms to run for slightly or completely different applications because of the assumptions and rules made to achieve the specific applications [5.2]. On the other hand, the configuration of the trees significantly alters the percentage of visible fruits on the tree. For tree row configurations, with a hedge appearance, the visibility of the fruit can reach 75%-80% of the actual number of fruits which is much better than the 40%-50% of visibility for conventional plantings [5.3].

One major difficulty in developing machinery to selectively harvest fruits is to determine the location, size and ripeness of individual fruits. These specifications are needed to guide a mechanical arm towards the target object. The computer vision strategies used to recognize a fruit rely on four basic features which characterize the object: intensity, color, shape and texture. Apart from these basic characteristics, many researchers are engaged with developing different approaches to recognize the fruits in natural background. Research works on the detection of different fruits and vegetables such as apple [5.4-5.7], cherry fruit [5.8], cucumber [5.9], orange [5.10-5.11], tomato [5.12-5.14], strawberry [5.15-5.16], melon [5.17-5.18] and sweet pepper [5.19-5.20] have been carried out. The detailed review on computer vision methods for locating fruits on trees is given by *Jimenez et al.* [5.21] and can be seen in Table 5.1which cover the main features of recognition approaches, sensing systems used to capture the images, the image processing strategies used to detect the fruit and result obtained of previous studies. Another comprehensive review was given by *McCarthy et al.* [5.22] on applied machine vision of plants with implications for field deployment in automated farming operations in which the research studies conducted previously were grouped into monocular vision with RGB camera, stereo vision and 3D structure, multispectral imaging and range sensing. Each group focuses on the recognition strategies and approaches under particular group and potential methods to enhance the machine vision system design for application to the agricultural field were discussed.

Kapach et al. [5.23] presented an ample review of classical and state-of-the-art machine vision solutions employed in harvesting robot systems, with special emphasis on the visual cues, computational approaches and machine vision algorithms used. The studies on image processing approaches for spherical and non-spherical fruits based on visual cues like color, spectral reflectance, thermal response, texture, shape etc. and based on machine vision algorithms like segmentation, clustering, template matching, shape inference, voting, machine learning etc., were discussed in detail according to the applications and algorithms developed by considering specific need for particular application. *Pal and Pal* [5.24] also reviewed and summarized the studies on image segmentation techniques focusing on fuzzy and non-fuzzy methods for color segmentation, edge detection, surface based segmentation, gray level thresholding and neural network based approaches. Adequate attention was paid to segmentation of range images, magnetic resonance images and quantitative evaluation of segmentation.

Table 5.1: Summary of reported vision systems for detecting fruit on trees [5.21]

Research group & References	Fruit[1]	Sensors and accesories[2] (image type)	Analysis method[3] (algorithm details)	Detects green fruit	Correct-false detections[4]
U.Virginia (Parrish77)	Appl	B/W+F (Spectral)	Local (Thr+FExt+RCla)	No	N.R.
MAGALI (D'Esnon87)	Appl	Color (Spectral)	Local (Thr)	No	N.R.
(D'Esnon87, Rabatel88)	Appl	3 Color+ 3 F (Spectral)	Local (Ratio+Thr)	Yes	50%-high%
U.Florida and USDA (Slaughter87)	Oran	Color+ L (Spectral)	Local (Hue&Sat+LCla)	No	100%-N.R.
(Slaughter89, Harrell89)	Oran	Color (Spectral)	Local (RGB+ BCla)	No	100%-N.R.
U.Purdue (Whittaker87)	Toma	B/W (Intensity)	Shape (Contour+CHT)	Yes	68%-42%
A.I.D. (Levi88)	Oran	Color+ F+ L (Spectral)	Shape (Gradient+TMat.)	No	70%-N.R.
Sunkist and U.Calif. (Sites88)	Appl & Pech	B/W+ F+ L (Spectral)	Local (Thr+FExt+LCla)	No	84%-20%
AUFO (Kassay92)	Appl	2 Color (Spectral)	Local (Thr+stereo)	No	41%-N.R.
CITRUS (Juste91)	Oran	B/W+ F+ 2L (Spectral)	Local (Thr)	No	80%-high%
(Juste91)	Oran	2 B/W+ 2F+ 2L (Spectral)	Local (Ratio+Thr)	No	80%-10%
(Juste91)	Oran	Color (Spectral)	Local (RGB+ BCla)	No	90%-5%
(Pla93)	Oran	B/W+ L (Intensity)	Shape (Convx+ Thr&Fitting)	Yes	75%-8%
U.Purdue and Volcani (Cardenas91)	Meln	B/W (Intensity)	Local (Thr+CExt+RCla)	No	84%-10%
(Dobrousin92)	Meln	B/W+ Air (Intensity)	Local (Thr+CExt+RCla)	No	80%-N.R.
(Benady92)	Meln	Laser&B/W+ Air (Distance)	Shape (Profile+CHT+RCla)	Yes	100%-0%
CIRAA (Buemi95)	Toma	Color (Spectral)	Local (Hue&Sat+ Thr+ stereo)	No	90%-N.R
U.College-London (Grasso96)	Oran	2 Color (Spectral)	Local (Thr+ CHT+ stereo)	No	86%-5%
AGRIBOT (Jimenez97, 98, 99)	Oran & spheres	Laser Range finder (Distance & Spectral)	Shape & Local (4 primitives+ ParaEsti)	Yes	80%-0%

[1] Appl=Apples, Oran=Oranges, Toma=Tomatoes, Meln=Melons, Pech=Peaches.

[2] B/W= Black and White camera, Color= Color camera, F= Optic filter, L= Artificial light, Air=Air blower to move leaves.

[3] Thr=Thresholding segmentation, FExt=Feature extraction, TMat= Template Matching, LCla=Linear classifier, BCla= Bayessian classifier, RCla=Rule-based classifier, RGB= Red-Green-Blue feature space, Hue&Sat= Hue-Saturation feature space, CHT= Circular Hough Transform, Gradient=Local gradient image, Convx= Convexity image, Profile=Profile image, ParaEsti= Parameter Estimation by CHT and sphere fitting.

[4] N.R.=No Reported.

5.1.2 Problem Identification

Image analysis and image processing are important applications used in decision support system during harvesting operation which help to extract the useful information from the scene. This information can be used to detect and locate the fruits on trees with the help of various parameters like shape, size, edges or color. Without information of fruits in terms of location and orientation, it is impossible for harvesting robot to perform the harvesting operation. At present, the several methods to detect the fruits on trees are available and the algorithm used to recognize fruits changes with physical, chemical or geometrical properties of fruits [5.21-5.24]. Also there are numerous ways existing for image processing and data analysis used in recognizing fruits which shows the importance of fruit recognition system in harvesting robot [5.25].

There are several problems that the previous research studies did not solved sufficiently and satisfactory which can be classified into two basic types: lighting and occlusion. The lighting factor could be a significant part of environment that formulates the problem as shown by previous several research studies. The amount of light available in the environment is dependent on sunshine, cloud cover and incident solar angle on the scene which can cause significant difference in how the harvesting scene appears. Also, the fruits inside the canopy receive a different amount of illumination compared with the fruits on the canopy surface. To deal with this type of problem, the image processing algorithm should be robust enough and efficient to handle this kind of lighting variations in the environment. The second problem, occlusion minimizes the fruit visibility area and disrupts the segmentation features that attribute to the detection. The main cause for this type of problem is leaves, branches and other fruits that overlap with target fruit. Unlike leaf or branch occlusion where there is a sharp contrast in color between the fruit and leaf, fruit occlusion can cause multiple fruits to appear as a single fruit.

On the other hand, apart from these problems, detection of fruits in natural background is difficult when color of fruits and background, such as the leaves and stems or fruits, are similarly greenish. As both, green sweet pepper and leaves has almost same color and due to that it is very difficult to recognize them separately during automatic harvesting in natural background. To distinguish the significant difference between leaves, stems and fruits with almost same color, the scene needs to develop a special type of algorithm which could be emphasizes the specific feature attributes for a particular kind of environment.

5.1.3 Objectives

As the green sweet peppers, leaves and stem has almost same color, the segmentation techniques like color, edge, size or shape could not be used to separate the green sweet peppers from natural background. At present, there is no perfect algorithm available for this purpose. Furthermore, though by using some segmentation techniques, the partial detection may be obtained; determining the 3D coordinates of detected fruits is a major problem or risk as partial detection might results in generation of false location and orientation. The output from recognition system like false detection of fruits or wrong positional information of fruit or poor performance of algorithm or interruptions in continuous and sequential processing of scene influence the overall performance of harvesting robot. Thus, by considering these facts and issues, the following objectives were taken into account:

1. The recognition system should be able to recognize and locate the fruits under conditions like: single fruit, fruits with leaves, fruits with leaves and stem.
2. The technique should be applicable in the situations where certain areas of the fruits are not visible due to partial occlusion by leaves or by overlapping fruits.
3. The recognition system should be robust enough for operating in the presence of difficult conditions like bright light reflections, shadows, variable lighting conditions, night operations and noisy background.
4. The recognition system output must supply the 3-dimensional position of the recognized fruit.
5. The developed algorithm must operate in real-time in a general purpose sequential processor with the support of special image processing boards.
6. To evaluate the performance of algorithm used for recognition of green sweet peppers and recognition rate by using same recognition system.

5.2 Recognition System for Green Sweet Peppers

5.2.1 Visual Sensing System

The image processing system consists of two microwave color CCD cameras, image grabbing unit and image processing software. For improving the fruit recognition rate, system was equipped with a circular ring of LEDs around camera neck to provide artificial lighting which helps to enhance the feature parameters [5.19]. A 5mm diameter LEDs used for artificial lighting were having light luminous intensity 25cd, forward voltage 3.4V and forward DC current 20mA. The microwave color CCD cameras [5.26] used for the system were high image quality CCD cameras with 680000 pixels, ¼ inches CCD sensor and 450 TV line resolution of RF System lab. The *PicPort* Leutron Vision color image frame grabber [5.27] was used to capture the real time images. For image processing, halcon software from MVTec [5.28] was utilized.

Figure 5.1 illustrates the block diagram of visual image sensing system. The left and right images were captured by left and right CCD cameras respectively and with the help of image capture board, images transferred to image processing program. In image processing program, the images were analyzed and processed with the help of halcon software and 3 dimensional (3D) coordinates were obtained. These coordinates sent to the robot control system and actuators were controlled by control system to move the end-effector towards the target location of the fruit. At this stage, visual feedback control system helps to reduce the errors in manipulation by sending the feedback of current position and comparing it with target position. When the target position achieved, the robot control program send the command to end-effector to grasp and detach the fruit from tree.

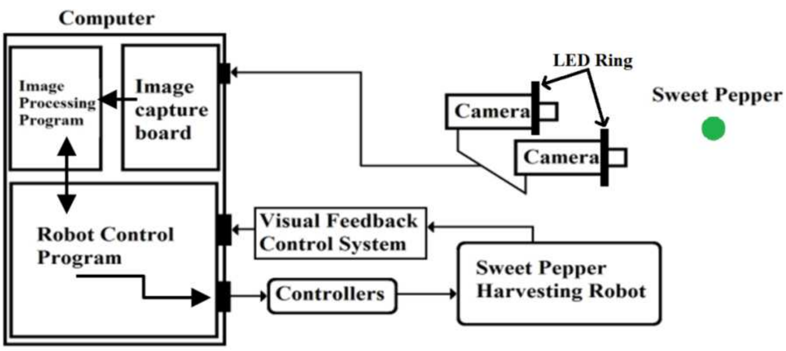


Figure 5.1: Block diagram of visual sensing system

5.2.2 Parallel Stereovision System

To perform the harvesting operation successfully, 3D coordinates of the target object must be known which could be given as input to the robot control system so that the robot arm would move to the target object and perform the operation. In this system, two CCD cameras were placed in parallel position so that left and right images could be obtained at same time with different view. During image processing, the horizontal and vertical coordinates can be obtained with the help of image processing software. To obtain the depth coordinate i.e. *Z* axis value, the parallel stereovision triangulation principle was used. Based on this principle, following equation was used to calculate depth value.

$$d = \frac{bf}{(xl - xr)} \qquad (5.1)$$

Where, d = distance between camera and fruit
b = distance between two cameras
f = focal length
xl and xr = X coordinates from left and right images respectively

The *X* and *Y* axis coordinates were obtained from left and right images captured during image processing while the *Z* axis coordinate was obtained with the help of Equation 5.1. The final 3D coordinates could be used to move the end-effector of robot arm towards target position with the help of control system. Figure 5.2 demonstrates the triangular relationship between left and right images used to calculate the depth value.

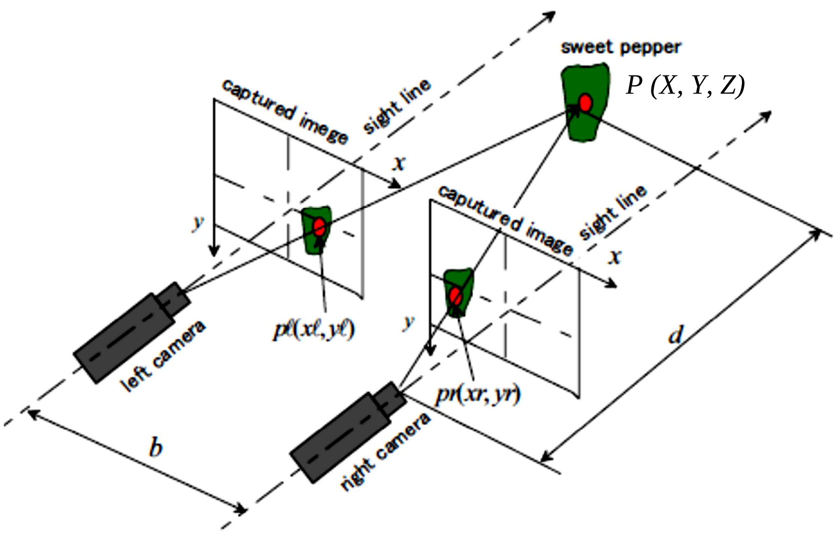


Figure 5.2: Parallel stereovision principle

5.3 Color Space models

For distinction of green sweet peppers, as size and shapes are irregular for almost all fruits, it was difficult to select features like size, shape, surface texture and edge extraction. Also, the color of fruits and leaves is almost same which further increases the complication for detection. Thus, by using artificial lighting and selecting the light reflection feature from fruit was considered as a better approach for distinction of green sweet peppers [5.20]. In case of green sweet peppers, artificial lighting provides considerable difference in reflections from stem, leaves and fruits which can be used as a key feature for recognition of fruits.

At present, 5 major color space models are being used in image processing for various applications viz. *CIE, RGB, YUV, HSL/HSV*, and *CMYK*. The *CIE* color model attempt to produce a color space based on measurements of human color perception and it is the basis for almost all the other color spaces. Based on the various parameters, 5 color space models were chosen for distinction of green sweet peppers as; *CieLab* which is based on human eye perception, *HSI* and *HSV* which are based on hue and saturation, *YIQ* and *YUV* which are based on luminance and chrominance. The lightness information from *HSI*, brightness information from *HSV*, chrominance information from *YIQ* and luminance information from *YUV* were supposed closely related to the reflection feature from image data and that was the main reason for selecting these models. As the images were captured in RGB color space model and there was no significant difference observed between fruit, stem, leaves and reflections from fruit and leaves, hence RGB color space was transformed into selected color space model during image processing using standard formulae for color space transformation.

5.4 Image Recognition Algorithm

For image processing, halcon software was used which has programming, operator and graphical interface for real-time image processing applications. When the process starts, two cameras capture the images and transfer them to computer to analyze the data. In the image recognition process, the images obtained from left and right cameras were analyzed to recognize the green sweet peppers in captured scene and to determine the location of green sweet peppers. A color making attribute parameters were used for binarization operation in each color space model followed by thresholding of images to reduce the area of interest. The operation was further repeated on reduced area of interest to detect the outline of fruit. The detected outline was then filled and labeled followed by numbering to avoid re-detection of same fruit. Figure 5.3 shows the outline of algorithm used for image processing to detect the green sweet peppers of color images obtained from CCD cameras.

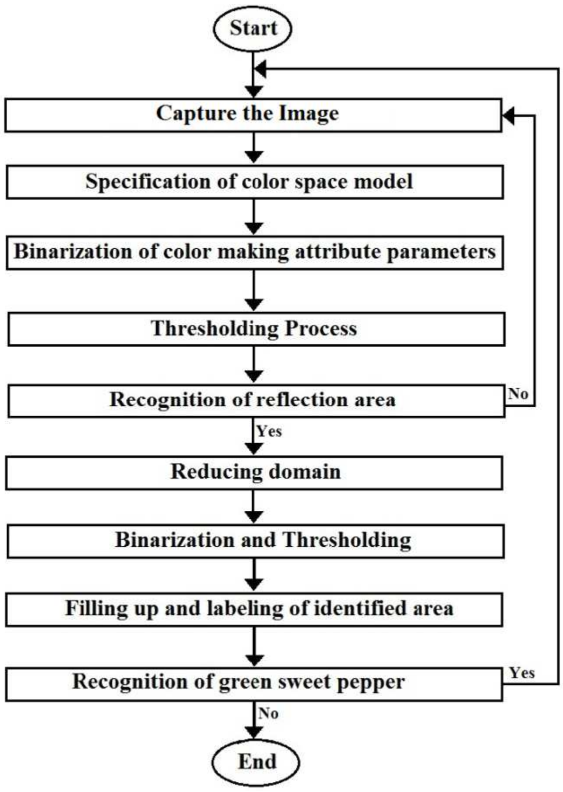


Figure 5.3: Image processing algorithm

After detecting green sweet peppers in the images, *X* and *Y* coordinates were calculated first in left image and then in right image respectively. *Z* axis coordinates were calculated by using parallel stereovision principle as shown in Figure 5.2. The sequential image processing flow chart can be seen in Figure 5.4. After finishing the detection process at one scene, cameras start to move further and capture other images and process them in the same way. This whole process was programmed in the software with looping so that continuous and sequencing image processing was possible. On the computer screen, the recognized fruits were displayed with their respective 3D coordinates and this data was saved in computer to use in control system for movement of end-effector.

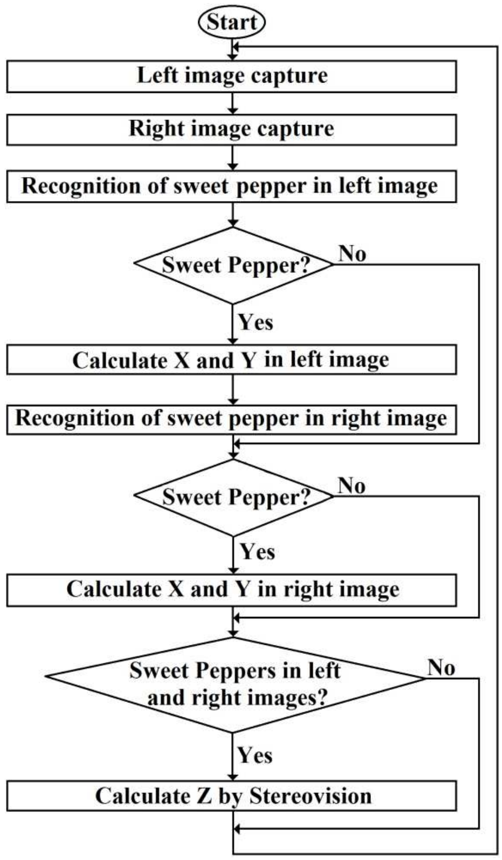


Figure 5.4: Sequential image processing flowchart

5.5 Experiments

To find out the most suitable and better color space model for recognition of green sweet peppers, during experiments, 5 color space models were selected as:

1. CieLab
2. YIQ
3. YUV
4. HSI
5. HSV

A set of 50 images were captured in RGB color space model using CCD cameras and artificial LED light during night time in order to avoid the effect of sunlight. Then captured images were transformed into each selected color space model, analyzed and processed for each color space model by using image processing algorithm as shown in Figures 5.3 and 5.4 with the help of halcon software to detect the green sweet peppers. In each color space model, the binarization process of colors was specified followed by thresholding operation. The final results were demonstrated by outlining the borders of detected area and displaying the 3D coordinated of the green sweet peppers which provide the location and orientation of fruit. At the same time, the data from images and final results of detection along with 3D coordinates were saved in the computer for further use. Figure 5.5 shows the left and right image captured during experimentation by CCD camera.

Figure 5.5: Left and right image captured by CCD cameras

Based on data obtained from image analysis and final results of detection with 3D coordinates, the color distribution of leaves and fruits were observed to confirm the reflection difference in between leaves and fruits. Also, color-ratio histograms were plotted to determine the separate distinction of green sweet peppers and green leaves. The relationship between actual depth and *Z* axis value computed by software, parallax disparity graph were plotted in case of best fitted color space model to confirm the accuracy of 3D coordinates provided by the halcon software. Finally, the rate of recognition was calculated based on the accuracy in the detection of green sweet peppers.

The visibility analysis was performed to determine the best fitted color space model for detection of green sweet peppers. In this analysis, the area of fruit detected by the image processing software was determined and the actual area of fruit in the image visible to human eyes was also calculated with the help of software. This analysis helps to determine the percent area detection of each fruit for every color space model selected and the results from this analysis provides the color space model with maximum percentage of fruit visibility detection.

5.6 Results and Discussion

In the image processing, thresholding of selected domain was more important as at this stage, the gray value difference of the fruit was found different than the leaves. This difference occurred due to the variation in the light reflectance by the fruits and leaves. The image processing by this way would help to choose the more efficient color space model for distinction of the green sweet peppers. Figure 5.6 illustrates the steps involved in the image processing of images obtained by CCD cameras in *HSV* color space model.

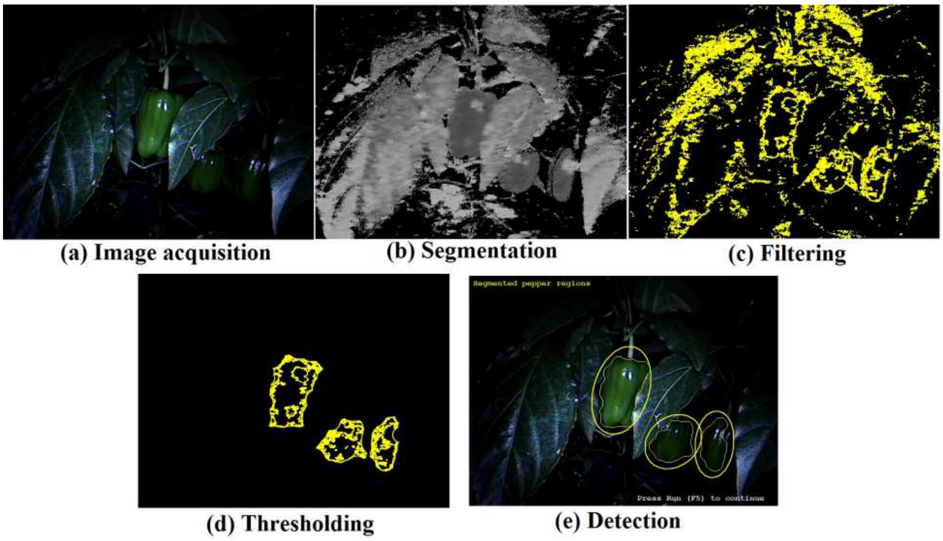


Figure 5.6: Image processing steps

5.6.1 CieLab Color Space Model

The *CieLab* color space model was developed based on perception of human eye in which the component *L* represents lightness whereas *a* and *b* for color-opponent dimensions based on nonlinearly-compressed *CIE XYZ* color space coordinates. Though *CieLab* color space was designed approximately uniform to human vision perception and having advantage of accurate color balance by using lightness, chroma and sometimes hue, this color space model was found not significant for detection of green sweet peppers. The reason for detection failure was the color attributes that falls outside the gamut of human vision which makes color space purely imaginary and could not be applicable for detection of green sweet pepper. According to the standard conversion formulae of *CieLab*, during the image processing of hue image, the division domain of the *f (t)* function should be linear [5.29]. Controversially, the division domain of the *f (t)* function was found non-linear during image processing which failed to match with values and slope factors of color components *a* and *b* resulting in failure of the detection. The information provided by *L* component which represents lightness was found correct but due to improper information given by *a* and *b* components which represents color-opponent dimensions, this color space model was found not significant for detection of green sweet peppers.

5.6.2 YIQ Color Space Model

In *YIQ* color space model, *Y* component represents luminance while *I* and *Q* together represent chrominance. The information on *IQ* parameters was a key factor in this color space model. To obtain the information on chrominance, the histogram equalization [5.30] was applied over *Y* channel and information from *I* channel was used for segmentation. After filtration and thresholding processes carried out, the results of detection of green sweet peppers were found not significant in some images. The detection of fruits by this color space was found in between 50 percent to 75 percent but complete detection of fruits was not possible. The information on luminance was found unstable during image processing and analyzed data were not enough to discriminate the green sweet peppers in the images as *YIQ* color space model only helped to normalize the brightness levels of the images.

On the other hand, in *YIQ* color space, the information from *I* channel was found highly sensitive to orange-blue than information from *Q* channel to purple-green. After normalizing the brightness levels of images; due to the sensitivity of *I* channel over *Q* channel, the complete detection of fruit was not possible. Enhancing the bandwidths for *Q* channel and decreasing bandwidths for *I* channel might help to improve the results.

5.6.3 YUV Color Space Model

The *YUV* color space model was considered good for enabling the perceptual brightness. The results obtained by *YUV* color space model were found not suitable for detection of fruits. Almost 50% of the images were failed to detect fruits while the images in which detection was possible, the detection was less than 25%. The main reason for the failure of detection was chrominance component. The information from *U* channel was found almost negligible which enhances the *V* channel brightness information increasing the chrominance level in the image. The luminance component was dominated by chrominance component which results in reduction of information on reflection feature.

5.6.4 HSI Color Space Model

An object oriented application of *HSI* color space model was found significantly useful in detection of the green sweet peppers. The information on reflection feature was considerably different for leaves and green fruits especially in hue image which helped to distinguish leaves and fruits separately. This color space model was found more suitable for detection of green sweet peppers as it provide correct information on wavelengths within the visible light spectrum, intensity of color in image and intensity of energy output of a visible light source. The thresholding process on *H* channel helped to reduce the area of interest in the image and select the reflection feature pixels given at thresholding value. The thresholding values in this color space lies between 40 to 90 and further normalization operation on *S* channel helped to enhance the purity or intensity of color. The information from *I* channel was found useful to decide the lightness of the pixels among the area of interest in the image.

When the green sweet peppers were overlapped or covered with leaves more than 50 percent, then the results were unstable and detection was not correct. This problem of misdetection was found due to the higher intensity of chroma component in *S* channel which dominate lightness information from *I* channel as the overlapped green sweet peppers or leaves reflect the light partially or with same intensity. In this situation, the reflection from green sweet peppers should be more than leaves but actually due to overlapping or covering, the fruits lead to mixing different intensities of features for fruits and leaves together. Also, the overlapped or covered fruits remain under shadow which increases the complications during image processing. Hence, even after thresholding operation on *H* channel, the intensity and lightness information was not enough to perform the detection.

In case of misdetection or false detection of fruits when they were overlapped, the two green sweet peppers were detected as one fruit and when covered by leaves, the detection includes leaf part of the plant along with partially detection of green sweet peppers. Thus, this color space model was found significantly suitable only for separated or single green sweet peppers without overlapping or covering by leaves.

5.6.5 HSV Color Space Model

The *HSV* color space model was found highly efficient in detection of the green sweet peppers. The brightness information from *V* channel has a good response to chroma in *H* channel. In hue image, the reflection feature has high brightness, high chroma and low intensity of energy output which separate the light reflected part from the image. This separation followed by thresholding the image for area of interest which enhances the feature properties. The high values of brightness and chroma helps to distinguish the reflection light area from the image and information from *V* channel on luminosity helped to decide the lightness or darkness of the image area. This leads to eliminating the darker area from image and selecting only lightness area as an area of interest. Further, the second thresholding operation on the area of interest distinguished the green sweet pepper and leaves separately. At this point, as the green sweet pepper and leaves had different reflection properties i.e. the reflection provided by fruit was more than the leaves. Hence, the information from *S* channel helped to decide the purity of color while information from *V* channel helped to decide the brightness area pixels. The connection operator selects all the pixels with same brightness and same chroma. Further, the labeling operator counts the object and records all the pixel values from selected region. Finally, filling up operator displayed the results by outlining the border of selected pixels.

HSV color space model was also found efficient when the green sweet peppers were overlapped or covered by leaves. In some cases, misdetection was occurred due to the high LED light intensity. The high intensity of LEDs increases the high values of intensity of energy output which dominate the information from *S* and *V* channels. This results in high brightness from the green sweet peppers and also from the leaves simultaneously which increase the chroma and brightness of the domain with high intensity energy output values. This enhancement of chroma, brightness and energy output intensity caused failure for discrimination of green sweet peppers. It was also found that if the sweet peppers covered by leaves or overlapped up to 70-80%, still *HSV* color space model provide almost stable results with proper recognition. If the green sweet peppers were covered by leaves or overlapped more than 80% then the results provide misdetection which includes some part of leaves or partial fruit detection or combination of stem, leaves and some part of fruit. The *HSV* color space model provides better results than *HSI* color space when green sweet peppers were overlapped or covered by leaves.

The results obtained from various color space models can be seen in Figure 5.7 while Figure 5.8 shows examples of results obtained for other images.

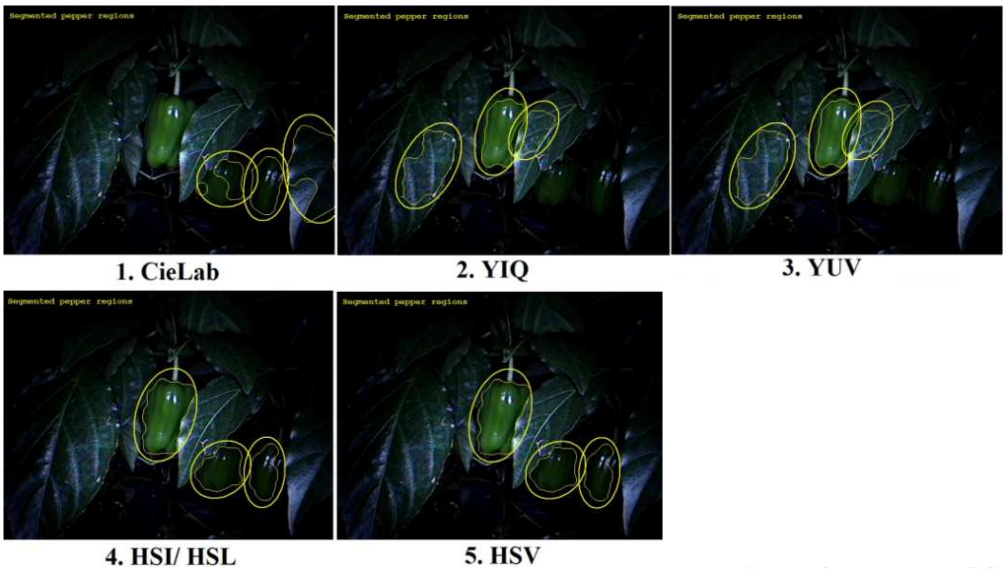


Figure 5.7: Various color space model results

5.6.6 Fruit Visibility Analysis

The fruit visibility analysis with percentage of detection for each color space model from set of 50 images processed was summarized in Table 5.2 with number of images. This fruit visibility analysis helps to determine the best fitted color space model for green sweet pepper recognition in natural background. For accurate detection, the fruit visibility should be higher than 75%.

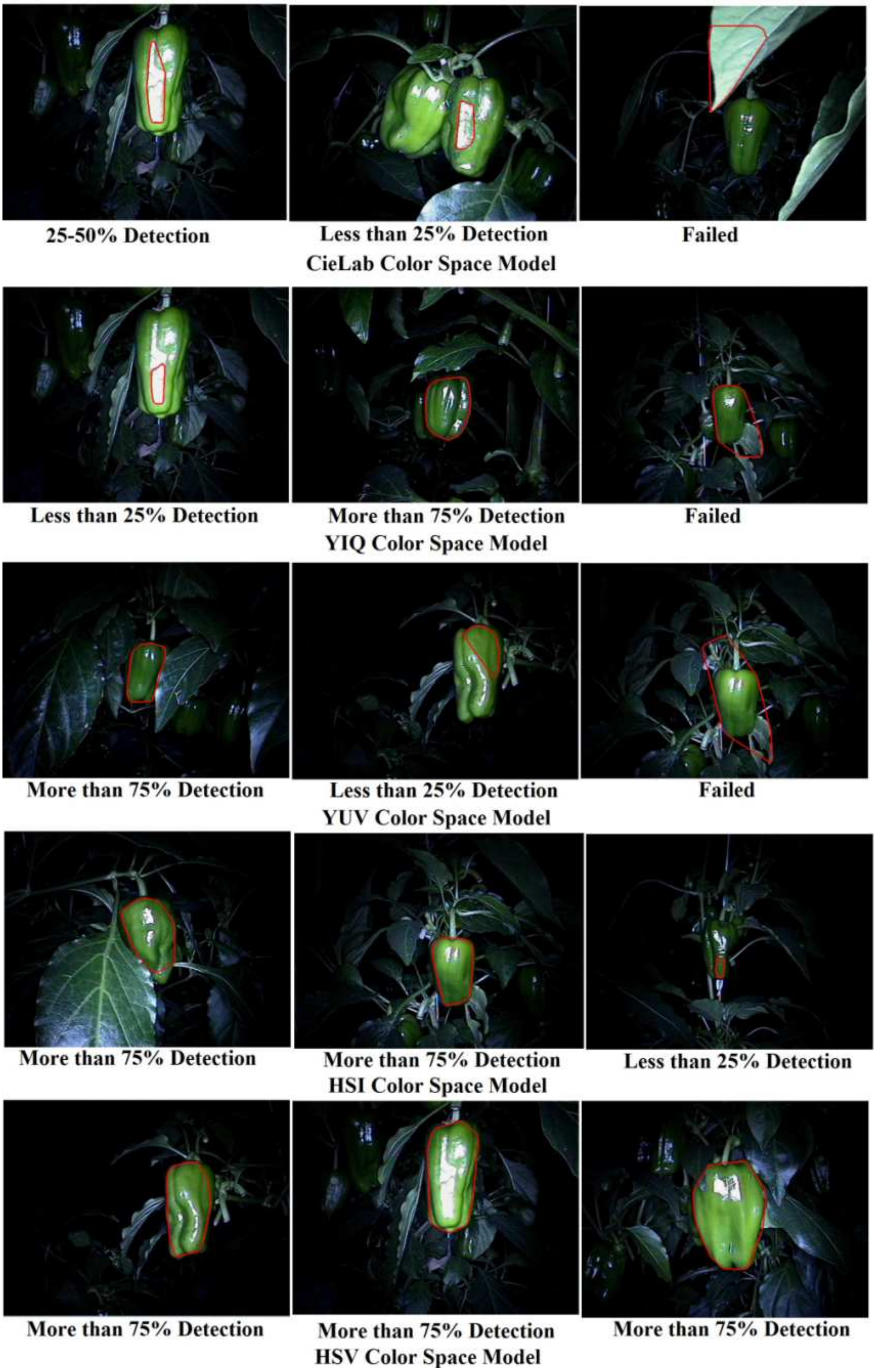


Figure 5.8: Examples of results

Table 5.2: Percentage of detection

	Detection of Green Sweet Pepper				
Color Space Model	**Less than 25%**	**25–50%**	**51–75%**	**More than 75%**	**Failed**
CieLab	26	9	2	0	13
YIQ	16	4	10	11	9
YUV	12	9	6	2	21
HSI	8	11	9	14	8
HSV	10	4	3	29	4

From above table, it was concluded that *HSV* color space model fits well for recognition of green sweet peppers followed by *HSI* color space model. All other color spaces were found not suitable for detection of green sweet peppers as the reflection feature parameter was not quantified by color making attribute parameters. Also, it was found that the color spaces based on hue and saturation shows better results for detection of green sweet pepper than color spaces based on luminance and chrominance. The *HSV* color space model shows high percentage of green sweet pepper detection and hence this color space model can be used for detection of green fruits in natural background by combining other feature parameters along with reflection feature.

Based on the results obtained from fruit visibility analysis, *HSV* color space model was selected as best fitted color space model for recognition of green sweet peppers and color distribution of leaves and fruits were observed in *HSV* color space model. Figure 5.9 demonstrates the color distribution of leaves, fruit and reflection feature in which reflection from fruit had higher histogram than reflection from leaves.

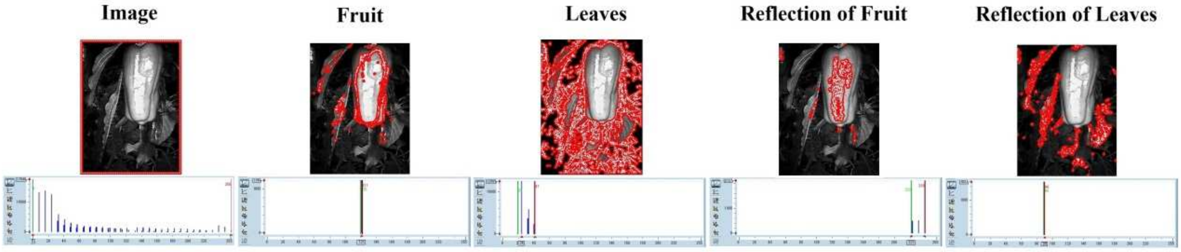


Figure 5.9: Color distribution of features in *HSV*

5.6.7 Comparison of HSV Color Space Model Histograms

In the *HSV* color space model, three different histograms were plotted from Hue, Saturation and Value channels to observe the feature attributes of an image. The reflection feature from fruits and leaves were analyzed in these histograms and can be seen in Figure 5.10. Both *H* and *V* channel differentiate the reflection feature accurately and reflection of fruits had higher histogram value than reflection of leaves while in *S* channel, reflection of fruits had lower histogram value than reflection of leaves. In the analysis, *V* channel found highly accurate than other channels to separate the feature attributes which helps to distinguish fruits and leaves separately.

5.6.8 Recognition Rate

Further, all the images captured by cameras were sorted into 4 groups to determine the fruit recognition rate. The 4 groups in which all the images were sorted were as follows:

1. G1: Fruit only
2. G2: Fruit with leaves
3. G3: Partially overlapped fruits
4. G4: Partially overlapped fruits and partially covered by leaves

These 4 conditions were found very natural and common in the greenhouse and it was decided that selecting these conditions for experiments may focus and demonstrate the actual effectiveness of each color space model, significant performance of the visual sensing system and efficiency and accuracy of developed algorithm for recognition system. Thus, by considering these facts, above mentioned 4 conditions were selected for the experiments. The images grouped were processed by *HSI* and *HSV* color space models as these models showed good fruit visibility results. Figure 5.11 demonstrates example of images categorized into 4 groups and respective results obtained by image processing software in which, the first row represents captured images while the second row represents recognition results of respective captured images into 4 groups.

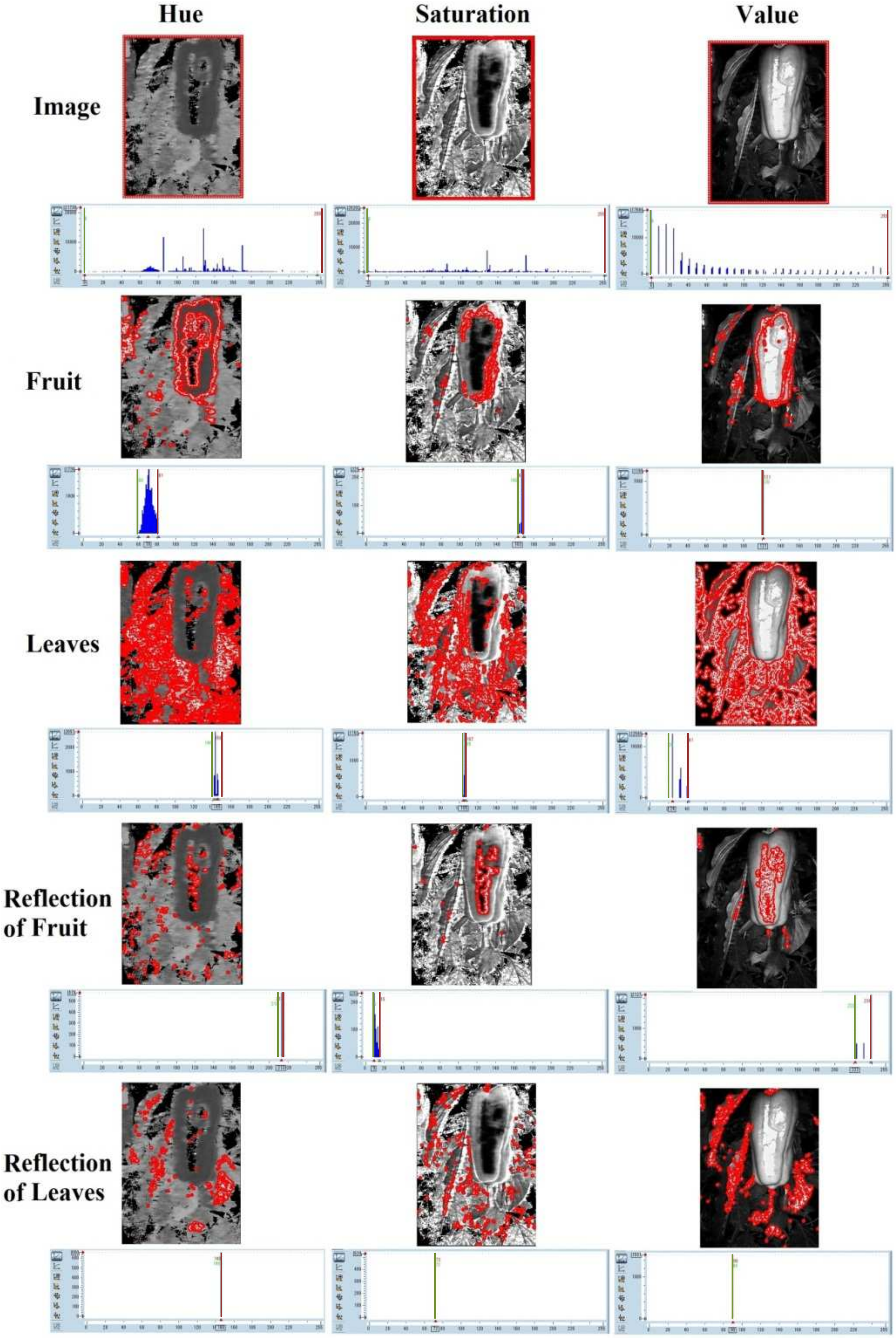


Figure 5.10: Comparison of Hue, Saturation and Value histograms in *HSV*

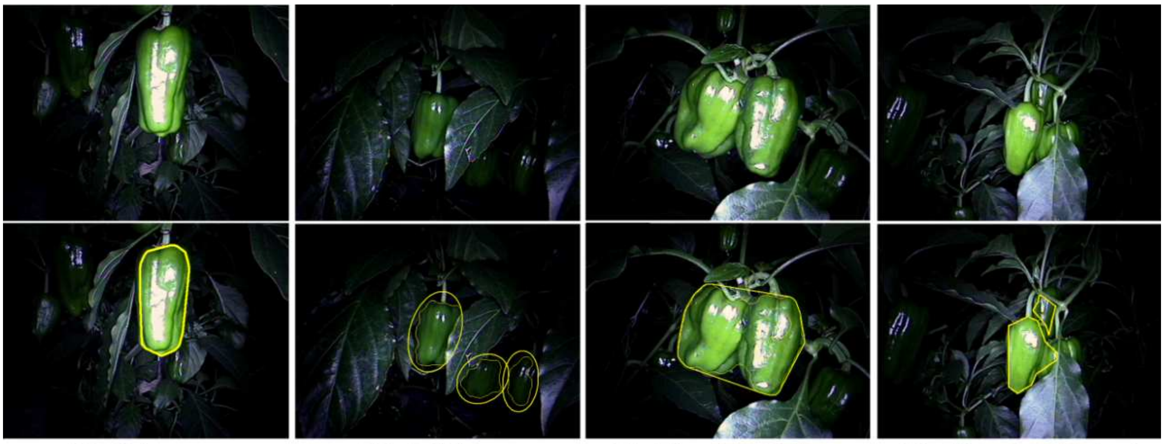


Figure 5.11: Examples of recognition results in four groups

For first two groups, recognition of green sweet pepper was found easier as there were no obstacles and fruits had high reflections than other part of images. For third group, if two fruits were overlapped then fruits were recognized clearly by outlining the shape of each fruit separately but represented as a cluster in the final results. Also, if one of the fruit had less reflection of light than other overlapped fruit, then the fruit which had maximum reflection of light was recognized by image processing software indicating only one fruit in the final results. This evidences the importance of artificial lightening and reflection of light in recognition of green sweet peppers. For fourth group, the recognition was quite harder than all other conditions as it increases the probabilities of false recognition due to increase in the complications of separating the color making attributes and reflection feature. Table 5.3 illustrates the recognition rate of the green sweet peppers for 4 groups mentioned above.

Table 5.3: Recognition rate for green sweet peppers

	Groups				**Total**
	G1	**G2**	**G3**	**G4**	
No. of Images	17	14	11	8	50
Recognition (*HSI*)	16	11	6	3	36
Recognition (*HSV*)	17	13	8	4	42
Recognition Rate (*HSI*), %	94.12	78.57	54.55	37.50	72
Recognition Rate (*HSV*), %	100	92.86	72.73	50	84

From above table, it was clear that *HSV* color space model had higher recognition rate in all 4 groups than *HSI*. Also, group G1 and G2 found significantly reliable for recognition of green sweet peppers while group G3 and G4 had less recognition rate. In both *HSI* and *HSV* color space models, the failure in recognition was occurred due to improper lightening, unsuitable distance between cameras and fruits and wrong image capturing angle. If the images captured by taking care of proper lightening, appropriate distance between cameras and fruits and suitable angle for image capturing then the false recognition could be reduced and recognition rate of green sweet pepper can be increased.

5.6.9 Location Accuracy of Recognized Fruits

After the successful discrimination of green sweet peppers, the 3D location of the fruits was determined with the help of image processing software. The *X* and *Y* coordinates were determined from the captured left and right images respectively while *Z* coordinates were determined by using parallel stereovision principle as mentioned in Figure 5.2. The program was developed to execute whole process starting from capturing images to displaying the 3D location of the recognized fruits in sequential process and program takes 1.8 seconds to execute the final results. The obtained 3D coordinates were saved in the memory for further use. The displayed images with 3D coordinate of the fruits in *HSV* color space model can be seen in the Figure 5.12 where the red circle in images represents center reference point of the fruit.

(a) Left Image with X_l and Y_l Coordinates **(b) Right Image with 3D Coordinates of Fruit**

Figure 5.12: 3D location image display of fruit in *HSV* color space

5.6.10 Depth Coordinate Accuracy

The obtained *Z* depth coordinates from software were compared with actual distance recorded between the camera and fruit during image capturing. The graph of actual measured distance and error distance based on distance obtained from image processing software for *HSI* and *HSV* color space model were plotted which can be seen in Figure 5.13. The graph was analyzed to determine the best distance between camera and fruit so that the recognition of fruits would carry out more precisely and the depth distance would be more accurate. The distance between two cameras kept constant to 100 mm during capturing all the images of green sweet peppers.

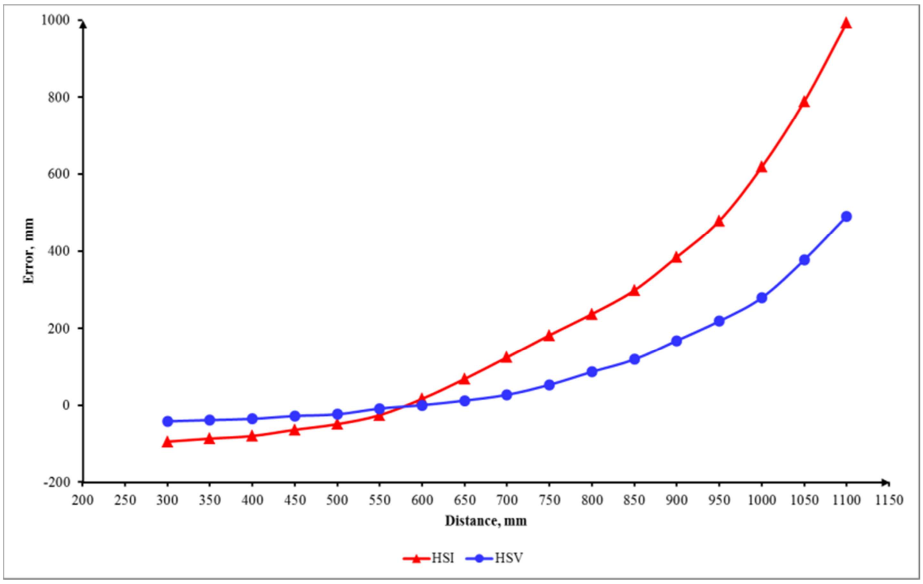


Figure 5.13: Errors in *Z* coordinates

The relationship between actual distance and distance measured by image processing software during image processing to detect the green sweet peppers was investigated and it was found that as the distance between cameras and fruit increases, the errors measured by software also increased. The variations in the depth coordinate errors were found significant in between *HSI* and *HSV* color space model. The depth coordinate errors in *HSV* color space model were less than *HSI*. In general, for 500 to 600 mm distance, the errors in depth coordinates were found very small while after 600 mm distance, the errors starts to differ significantly. For *HSV* color space model, at 600 mm distance, the error was 0.2 mm while for *HSI* it was 14 mm. Hence, by adjusting the distance between cameras and fruit at 600 mm, the accuracy in depth coordinates can be achieved in *HSV* color space model.

5.6.11 Parallax Errors

The relationship between disparities *(Xl-Xr)* and distance to fruit was also analyzed to inspect the parallax errors in the results obtained from the image processing software. This relationship can be seen in Figure 5.14.

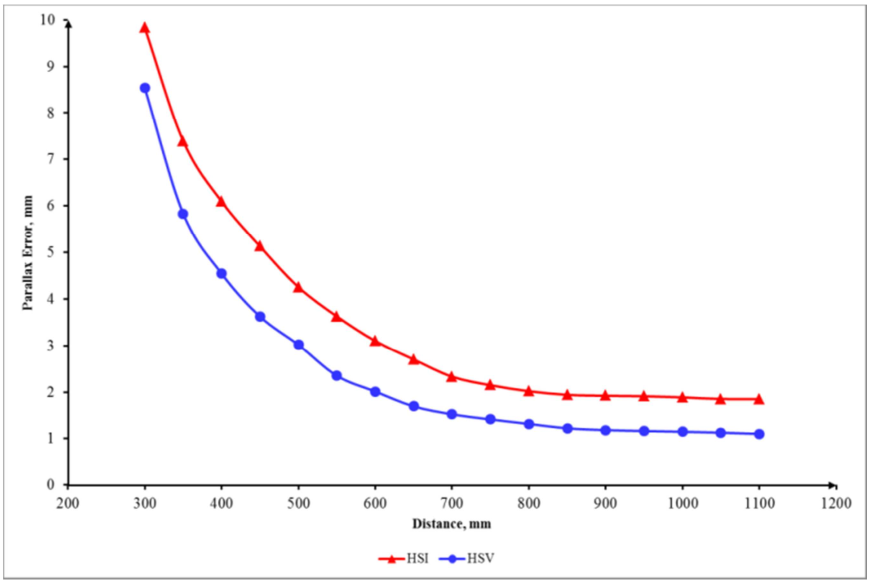


Figure 5.14: Parallax errors

For both color space models, the parallax errors were high for smaller distances and then start to reduce gradually and at the end became almost constant. The parallax error disparities were high in *HSI* color space model compared with *HSV* which shows that the images processed by *HSV* color space model provides better results and less parallax errors than *HSI* color space model. In *HSI* color space model, 9.85 mm parallax error was observed at 300 mm distance and 1.85 mm at 1100 mm distance. In case of *HSV*, 8.53 mm parallax error was observed at 300 mm distance and 1.10 mm at 1100 mm distance. For the distance at which *Z* axis coordinate errors were found minimum, i.e. from 500 mm to 600 mm, the parallax errors were found as 4.2 mm to 3.1 mm in case of *HIS* and 3 mm to 2 mm in case of *HSV* color space models respectively.

The parallax errors relationship with distance between camera and fruits shows that, increase in the distance reduces the parallax error disparities but increase the *Z* axis coordinate errors while reducing the distance increases the parallax error disparities and reduces the *Z* axis coordinates errors.

5.6.12 Fruit Stem Inclination and Stem Height

To ensure the orientation of detected sweet peppers, a small algorithm was developed which could calculate the detected fruit stem angle with respect to vertical axis and fruit stem length. The fruit stem angle and fruit stem length helps in the grasping and cutting operation by determining the grasping points and cutting point by matching with pre-set height of cut parameters. The developed algorithm uses low pass filter segmentation and thresholding to detect the stem angle and then measures the fruit stem angle and length. Figures 5.15- 5.17 shows the final results of recognition system where the first image in display shows left image and left coordinates; second image shows right image with left, right and 3D coordinates while third image shows final results of recognition system along with left, right and 3D coordinates and fruit stem angle and fruits stem length.

Figure 5.15: Location and orientation of sweet pepper I

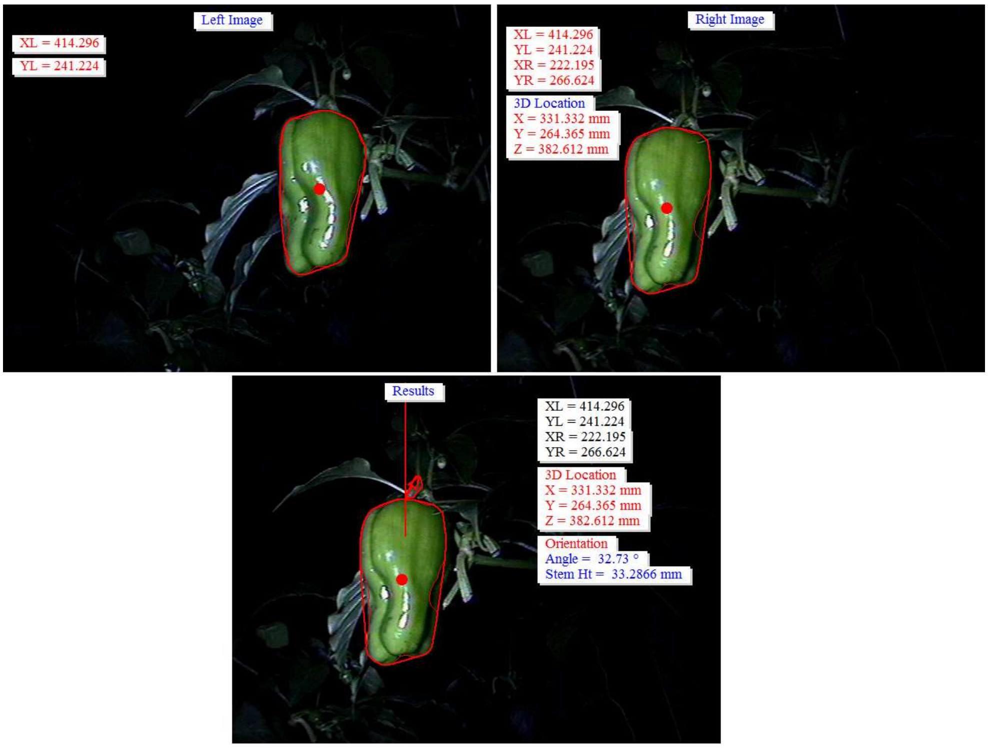


Figure 5.16: Location and orientation of sweet pepper II

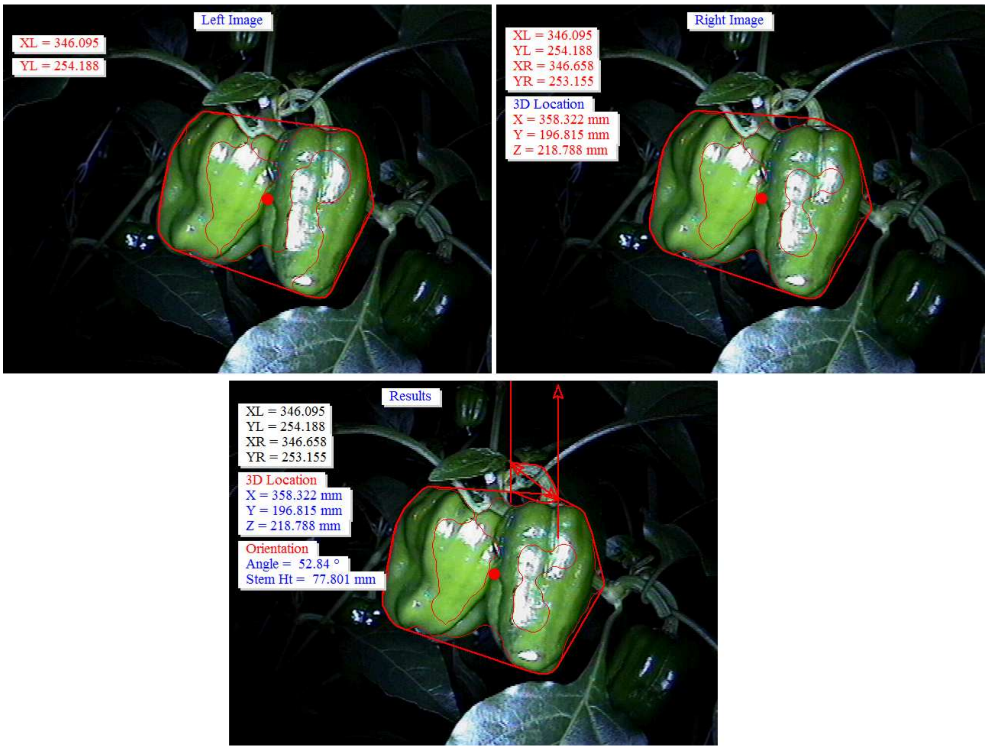


Figure 5.17: Location and orientation of sweet pepper III

5.7 Conclusions

Based on color making attributes and reflection feature, various color space models were tested to determine the suitable color space model for detection of green sweet peppers. For color images, *CieLab, YIQ, YUV, HSI and HSV* color space models were selected for image processing. In case of color images, *HSV* color space model was found more significant with high percentage of green sweet pepper detection followed by *HSI* as both provides information in terms of hue/lightness/chroma or hue/lightness/saturation which are often more relevant to discriminate the fruit from image at specific threshold value. In *HSV* color space model, high brightness, high chroma and low saturation which separate the light reflection feature of fruits from the image was an advantageous point for distinction of green sweet pepper. Also, in *HSV* color space model, the reflection of light from fruits had higher histogram than reflection of light from leaves which helps to distinguish green sweet pepper and green leaves separately in natural background. Further, the overlapped fruits or fruits covered by leaves can be detected in better ways in *HSV* color space model than *HSI*.

The *YIQ* model could be useful for detection if the bandwidths of *Q* channel raised higher that dominate the effect of luminance and increase sensitivity to purple-green than bandwidths of *I* channel.

The recognition rate was found higher for *HSV* color space model as 84% while for *HSI* as 72% which was further categorized into 4 different groups based on various conditions that occurs during harvesting process. Computation of 3D coordinates of recognized sweet peppers was also conducted in which halcon image processing software provides location and orientation of the fruit accurately. The depth accuracy of *Z* axis was investigated in which 500 to 600 mm distance between cameras and fruit was found significant to compute the depth distance precisely when distance between two cameras maintained to 100 mm. The minor errors in parallax disparities can be corrected by using visual feedback control system during harvesting operation. The orientation and stem height of detected fruit was computed successfully which helps to decide the grasping and cutting points during the picking operation.

As the research methods presented in the paper provides significant results on recognition and computation of positional information of green fruits in natural background, adopting this type of research for other agricultural fruits has three distinct perspectives: first, determining the optimal color space model for each individual fruit; second, applying the same color space model for all agricultural products as a universal solution and third, combining the color space models that have significant effect on color attributes and features of fruits to be detected. In first case, the fruit recognition rate will be highly increased while the method will be time consuming as it needs lots of time to collect; process and analyze the data and draw the conclusions. Applying this type of research for major agricultural fruits will widen the scope for fruit harvesting robots. In second case, the time can be saved but the recognition rate will be decreased and accuracy of detection will be low as every fruit has considerable aspects and changes in physical and chemical properties. In third case, to find out optimal combination of color spaces will be a big challenge for researcher and needs sophisticated research which will not only increases the detection accuracy but also could be used as a universal solution to detect the fruits in natural background.

Chapter VI

RECOGNITION SYSTEM: II MULTISPECTRAL IMAGING

6. RECOGNITION SYSTEM – II

Multispectral Imaging

This chapter explains the multispectral imaging recognition system used in detection of the sweet peppers. The recognition system described in this chapter was based on multispectral imaging processing which help to locate the fruits on trees. Several types of infrared optical filters were used to evaluate the recognition system. The results were presented demonstrating the variations in the multispectral wavelengths to detect the sweet peppers based on various features. This chapter further also demonstrates the algorithm developed to determine the maturity of detected sweet peppers. The maturity of sweet peppers was evaluated by using the most significant infrared optical filter that shows efficient performance for sweet pepper detection.

6.1 Introduction

6.1.1 Background

Multispectral Imaging is a technique for recognizing and characterizing physical properties of materials using the principle of the varying absorption (or emission) of different wavelengths of light by the objects. This technique has been applied in areas of science such as medicine, forensics, geology, and meteorology. The wavelengths of light used in multispectral imaging usually lie within the Infrared (IR) and Near Infrared (NIR) ranges. In contrast to hyperspectral imaging, which characterizes materials by measuring the variation in light intensity over continuous ranges of wavelengths, multispectral imaging utilizes a relatively small set of specific wavelengths. The desired wavelengths may be selected by a set of dichroic interference filters of specific wavelength and pass-band. The variation of light intensity verses wavelength is measured by means of appropriate sensor techniques for each point in the scene being imaged. This technique was originally developed for space-based imaging and can allow extraction of additional information the human eye fails to capture with its receptors for red, green and blue. For different purpose, different combination of spectral bands can be used representing by red, green and blue channels. Mapping of bands to colors depends on the purpose of the image and the personal preferences. For the last few decades, NIR spectroscopy has shown considerably promising results for the non-destructive analysis of food products and is ideally suited for on-line measurements in the agrofood industry due to its advantages: minimal or no sample preparation, versatility, speed and low cost analysis [6.1].

Most of well-known applications of NIR spectroscopy in fruits have focused on the quantitative prediction [6.2] of chemical composition, internal damage and ripening stage in various fruits such as kiwifruit [6.3-6.4], apple and mango [6.5-6.6], cherry [6.7], grape [6.8], plum and nectarine [6.9] and dates [6.10]. The use of multispectral-image-based perception methods has been studied extensively to assess the crop nutrition level based on crop canopy reflectance in multiple spectral bands [6.11-6.12]. Optical properties based on reflectance, transmittance, absorbance, or scatter of light by the product often related with features and are chosen for various purpose such as external qualities like shape, color, defect; internal qualities like flavor, texture, nutrition, defect, pH level, total soluble solids content, dry matter, sugar content, nitrogen level, starch, moisture content, essential oil content, different acids, chlorophyll etc. The detailed review on the determination of various non-destructive measurement of fruits and vegetables quality by means of NIR techniques was given by *Osborne et al.* [6.1], *Nicolai et al.* [6.2], *Abbott* [6.13] and *Grift et al.* [6.14]. The potential of NIR spectroscopy and imaging as rapid, non-destructive and multi-parametric technique makes most of its applications on fruits and vegetables quality measurement intact including not only food industry, post-harvest applications but also horticultural crops.

6.1.2 Problem Identification

In last few decades, in NIR technique, most of the work has been done either on quality determination, quality inspection and measurement applications or on post-harvest applications as mentioned in above section. Though NIR technique has shown significant results for non-destructive quality measurements of fruits and vegetables delivering satisfactory application development for quality measurement, inspection and post-harvest operations, still there is not enough research has been done on NIR multispectral imagining for detection purpose. *Czarnowski and Cebula* [6.15] investigated the spectral properties of red, green, yellow and cream colored sweet peppers. The relationship between spectral properties of fruits and leaves was studied and the results showed that up to 700 nm the fruit and leaves had almost same reflectance and absorbance of light while after 700 nm to 1100 nm there was significant difference between reflectance and absorbance. *Van Henten et al.* [6.16] studied the possibilities of adoption of spectral properties to detect the cucumber in natural background. Two monochrome cameras were used with 850 nm and 970 nm band-filters simultaneously. The spectral band filters showed better detection results as significant difference was found between the spectral properties of cucumber and leaves. *Hemming* [6.17] used the same vision system [6.16] to study the possibility of detection for sweet peppers. The study reported that the spectral vision system can be used successfully for detection of sweet peppers. *Bulanon et al.* [6.18] used a CCD camera with six band pass filters to examine the possibilities of multispectral imaging for citrus fruits detection. 600 nm, 650 nm and 700 nm band pass filters were found suitable to separate the citrus fruits from background.

Based on detailed review of multispectral spectroscopy and imaging, it was decided that to test the possibilities of adoption of multispectral imagining method for sweet pepper harvesting robot vision system. The main purpose of this chapter in this research was to combine the two tasks: first use the multispectral vision system for detection of sweet peppers and second use the same vision system for non-destructive quality determination of sweet peppers. Although the recognition system mention in chapter 6 shows very effective and significant results on detection of green sweet peppers by using color imaging, there are possibilities that the robot manipulator could harvest un-matured sweet peppers after successful detection which will not only reduce the market cost of product but also it would result in imperfect automatic harvesting system. By considering these facts and understanding the need of multispectral imagining research scope for sweet peppers, this research was carried out. This multispectral imagining system could highlight the importance of NIR technique for not only non-destructive quality measurement and inspection but also significant recognition system for sweet peppers. On the other hand, this will built-up and enrich the research on NIR multispectral imagining technique for multi-task purpose.

6.1.3 Objectives

By considering the need of efficient and effective multispectral recognition system, the main objective of this chapter was decided as to develop and evaluate the multispectral recognition system for sweet peppers not only to detect the fruits but also to determine the maturity of detected fruits. The detail specific objectives were as follows:

1. To develop a multispectral recognition system and investigate the possibilities of discrimination of sweet peppers in natural background by using various IR wavelength band optical filters.
2. To develop algorithm for multispectral recognition system which should be able to recognize and locate the fruits under conditions like: single fruit, fruits with leaves, fruits with leaves and stem.
3. To evaluate the performance of multispectral recognition system for situations such as occluded fruits or fruits covered by leaves and hard to visible.
4. The multispectral recognition system must not be influenced by variable field conditions such as bright light reflections, shadows, variable lighting conditions or noisy background.
5. To develop algorithm to determine the maturity stage of detected sweet peppers based on non-destructive quality measurement techniques by using various optical filters.
6. To evaluate the performance of multispectral recognition system by composing detection algorithm and maturity detection algorithm together to form a multi-task recognition system environment.
7. To compute the recognition rate, fruit visibility analysis and maturity detection analysis of detected sweet peppers.

6.1.4 Limitations of Multispectral Recognition System

The limitation for the multispectral recognition system use would be both chemical constituents to be measured and the physical problems associated with light reflectance and transmission through the fruit. The IR imaging system can be used to detect only chemical compounds which contain CH, OH or NH groups. Identification and quantification of the compounds must be worked out by a computer and software capable of carrying out the complex statistical mathematics. As fruit is mainly water, differentiation between water and chemical constituents of interest can be difficult.

The orientation of the fruit to the light inclination angle and camera angle used to capture the images might also be a circumstantial limitation. The non-destructive qualitative measurement techniques related to color pigments of fruits might have influence of day time and night time of the same day which needs precise calibrations for day time and night time optical properties influence.

6.2 Multispectral Recognition System for Sweet Peppers

6.2.1 Visual Sensing System

The visual sensing system of multispectral recognition system consists of *Logitech quickcam pro 4000* cameras, 4 infrared (IR) optical filters and 5 mm diameter IR LED ring. The cameras were integrated with modifications that facilitate the replacement of visible filter by IR optical filters and changing the optical filters as per the experimental set up. The cameras were connected to the computer by USB interface and halcon software was used for image processing. The IR LEDs used for artificial lighting having forward voltage 1.25 V, forward DC current 25 mA and 940 nm wavelength intensity. 4 IR optical filters were used for the experiments: IR 78, IR 80, IR 90 and IR 96 where the number of IR filter represent the wavelength such as IR 78 represents 780 nm, IR 80 represent 800 nm wavelength and so on.

During each experiment, appropriate IR optical filters were installed in the cameras. The images were captured with the help of cameras and IR artificial lighting. The LED ring can provide artificial lighting from 1 LED or combination of 1 increment of LEDs out of 4. This means, the experimental set up can capture one same scene with 5 conditions: no LED, 1 LED, 2 LEDs, 3 LEDs and 4 LEDs. This would help to investigate the effect of artificial IR lighting on the optical properties and detection of sweet peppers in natural background. The captured images were transferred to computer and processed in halcon image processing software which helps to analyze the data and locate the sweet peppers from the scene. Figure 6.1 illustrates the block diagram of visual image sensing used in multispectral recognition system.

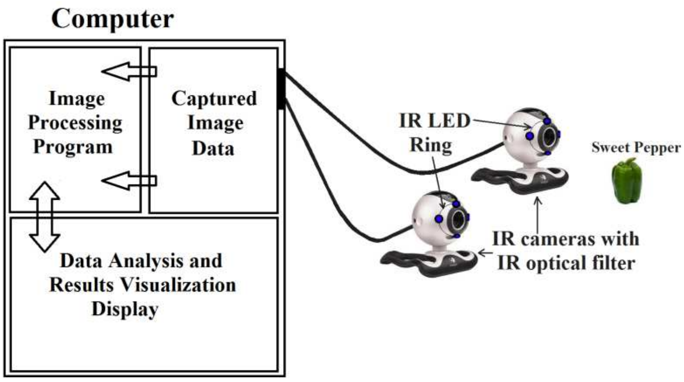


Figure 6.1: Visual sensing system

6.2.2 Image Processing Algorithm

The detection of small targets in cluster is a problem of critical importance to fruit harvesting robotics. Multispectral IR imaging technique have been effective for improving small target detecting some forms of camouflaged targets and other targets using false coloring. To investigate the possibilities of detection of sweet peppers by IR optical filters, the algorithm developed for detection operation in image processing can be seen in Figure 6.2.

The algorithm consists of several operations and filters that help to confine the areas of interest in the images. The image was captured and transferred to computer where the algorithm performs these operations: The histogram equalization was applied on captured image so that the images would normalized by removing the surplus noise from image. The normalized images then processed with global transformation operation by using SKL (Sequential Karhunrn-Loeve) [6.19] filter for approximating the images by low dimensional subspace. This operation also helps to minimize the mean statistical errors between area of interest and their projections in the subspace. Further, the images were segmented and binarized followed by thresholding operation. The thresholding values were decided based on the segmentation and filtering of an image using global thresholding. Threshold selects the pixels from the input image whose gray values *g* fulfill the following condition:

$$MinGray <= g <= MaxGray \quad (6.1)$$

Where *g* was defined as: a thresholding pixel *g (x, y)* of an image whose *f (x, y)* was:

$$g(x,y) = \begin{cases} 1 & if\ f(x,y) \leq T \\ 0 & if\ f(x,y) \geq T \end{cases} \quad (6.2)$$

Where *T* was a specific thresholding value of target object

All points of an image fulfilling the condition are returned as one region. If more than one gray value interval is passed (tuples for *MinGray* and *MaxGray*), one separate region is returned for each interval. The value of *g* can be defined by user after observing the visualization of variation of *g* on input image. After thresholding, the domain area was reduced and smoothened followed by filling up and labeling the identified area. This identified area represents the presence of sweet peppers in the images. If any operation in the algorithm fails then all further operations automatically becomes invalid and hence also fails to detect the sweet peppers in the input image.

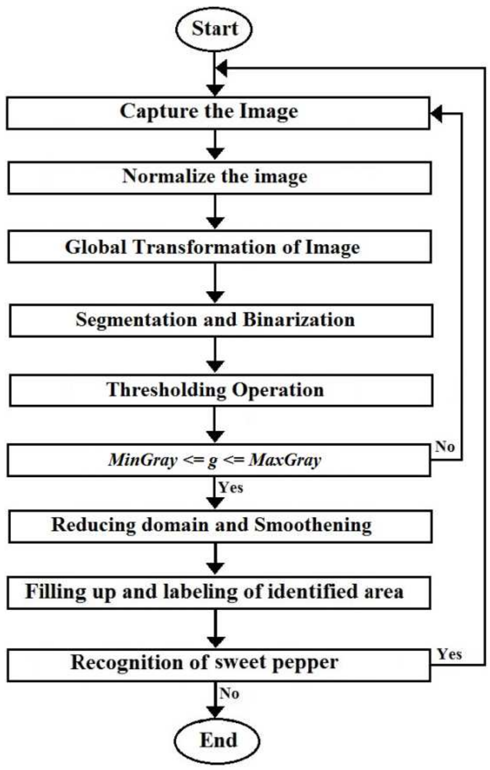


Figure 6.2: Multispectral image processing algorithm

6.3 Experiments

To test and evaluate the performance of multispectral IR imaging recognition system, 4 different types of IR optical filters were used as follows:

1. IR 78 optical filter – 780 nm wavelength
2. IR 80 optical filter – 800 nm wavelength
3. IR 90 optical filter – 900 nm wavelength
4. IR 96 optical filter – 960 nm wavelength

The color filters were replaced by IR optical filters in the cameras and cameras were equipped with IR LED artificial lighting. The lighting circuit was designed to illuminate 1 or combination of 1 LEDs up to total 4 LEDs. The whole set was connected to the computer as described in the visual sensing system. As the artificial lighting consists of IR LEDs, the illumination by naked eyes was not possible. Figure 6.3 shows the camera with IR 90 optical filter and artificial IR lighting used during experiments.

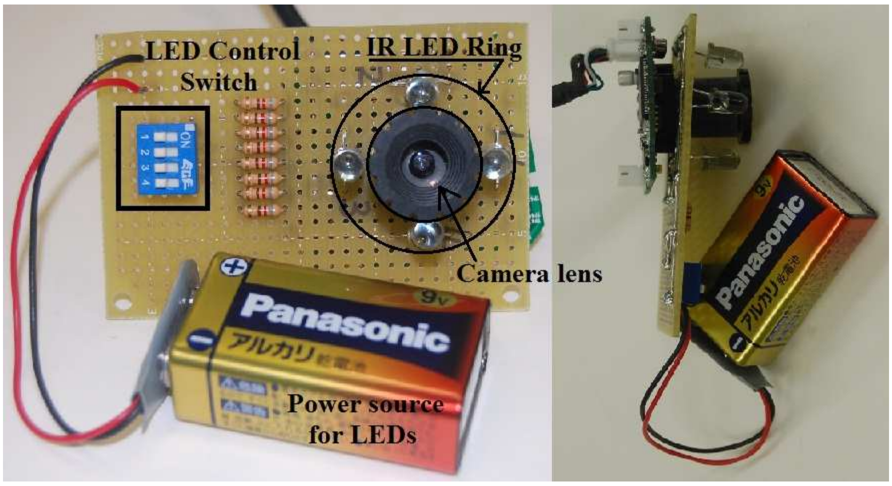


Figure 6.3: Camera with IR artificial lighting

The experimental images were categorized into 4 groups as mention in Chapter 5 section 5.6.8. These 4 groups were as follows:

1. Group G1: Fruit only
2. Group G2: Fruit with leaves
3. Group G3: Partially overlapped fruits
4. Group G4: Partially overlapped fruits and partially covered by leaves

By using IR optical filters, several numbers of images with different conditions were captured. Also, at the same time, artificial lighting conditions also changed from no light to 4 LEDs illuminated. The captured images were then transferred to the computer for image processing. The image processing was carried out by using algorithm mentioned above to obtain the image data and detection results. The visibility analysis was performed to determine percent of detection of sweet peppers. In this analysis, the area of fruit detected by the image processing software was determined and the actual area of fruit in the image visible to human eyes was also calculated with the help of software. This analysis helps to determine the percent area detection of each fruit under every selected condition and maximum percentage of fruit visibility detection. To test the possibilities of sweet pepper detection and to evaluate the multispectral recognition system, various experimental conditions defined during experiments can be seen in Figure 6.4.

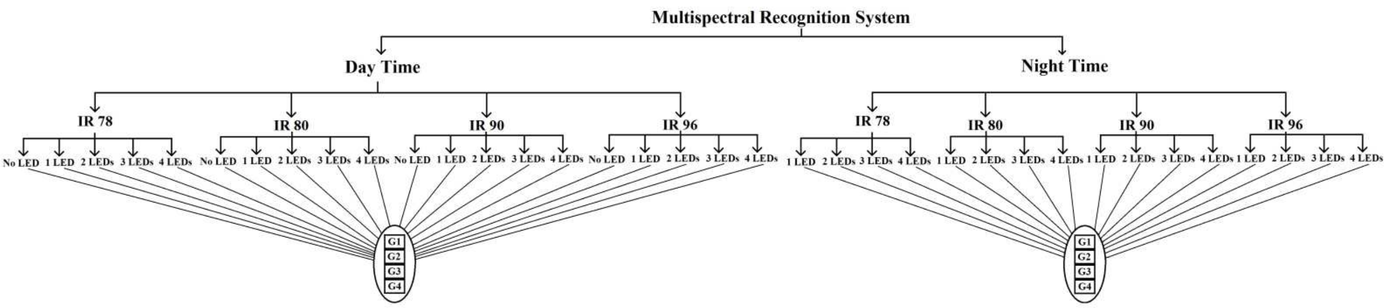


Figure 6.4: Experimental parameters

6.4 Results and Discussion: IR 78 Optical Filters

The captured images were processed according to the image processing algorithm developed for detection of sweet peppers. Figure 6.5 shows the day and night time images captured with 4 LEDs during experiments under group G2.

Figure 6.5: Images captured under G2 with 4 LEDs: day time (left), night time (right)

The results of IR 78 optical filter obtained by image processing under various conditions can be seen in Figure 6.6 representing conditions used during experiments.

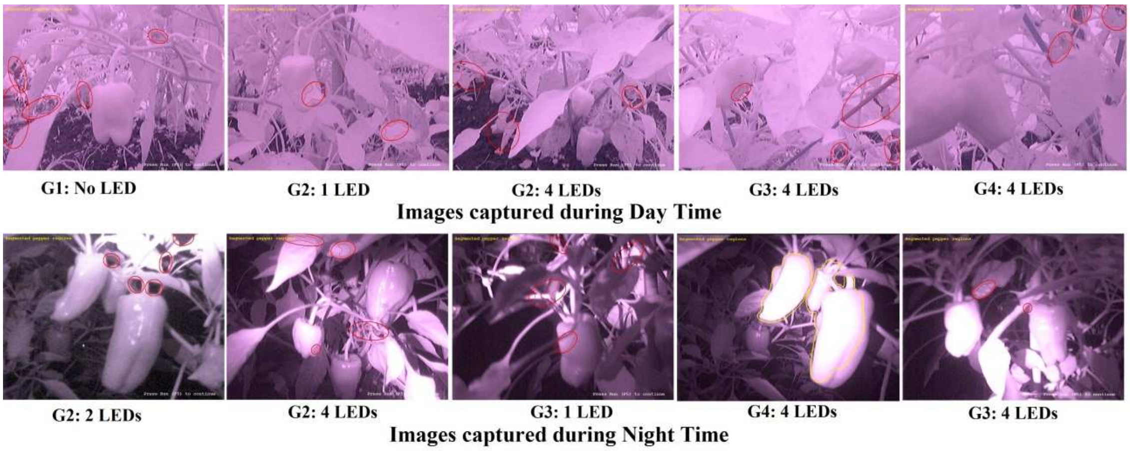


Figure 6.6: Recognition results by IR 78 optical filter

By using IR 78 optical filter, there were no significant sweet pepper detection results observed. Though, in some cases, there was detection of fruits but the results were unstable. In case of images captured during day time, it was found that, artificial IR light does not had any effect on detection, rather there was no feature occurred which could be used as asset for detection such as reflection from fruit surface. In all 4 groups and selected conditions, the multispectral system was not found effective to detect the sweet peppers. Also, the color of fruits was same as that of leaves and stems. Even in some cases, it was difficult to distinguish fruit and leaves. Based on the results obtained from image processing, it was concluded that IR 78 optical filter cannot be used for sweet pepper detection in day time. This might be due to the sun light effect which has higher IR wavelength lighting than the artificial IR lighting used during experiments.

In case of images captured during night time, it was observed that, the artificial lighting had significant influence on the detection. In some cases, the detection was possible but the percentage of false detection or no detection was higher. For detected images, after analysis, it was concluded that the detection was due to only high brightness and chroma components received from artificial lighting. The detection was not possible due to any feature attribute, rather when the artificial light intensity reduce, the same images failed to detect the fruits.

To verify the feature attribute feasibility, the histogram analysis was done on images captured during night time and can be seen in Figure 6.7.

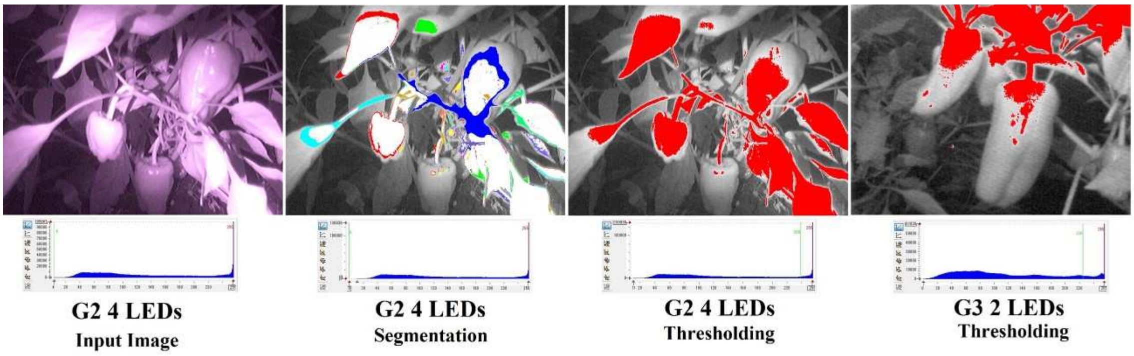


Figure 6.7: Histogram analysis for IR 78 optical filter

From above figure, it was investigated that there was no feature attribute feasibility for detection of fruits during image processing. The results only help to decide whether image was darker or brighter in nature. During thresholding process, selected threshold value failed to provide detection, instead only highlight the high intensive area in the image. In most cases, the detection was occurred when 4 LEDs were used but still the results were not precise and contained background part of fruit plant parts. As the intensity of light was high, there were also strong shadows observed which increased the false detection. For night time images, partial or detection with fruit plant parts was possible with G1 and G2 when 4 LEDs used.

Thus, based on the results obtained, it was concluded that IR 78 optical filter cannot be used for detection of sweet peppers in night time also. This was due to the high brightness and chroma caused by high intensity of artificial lighting. So IR 78 optical filter can be only used to analyze the darkness or brightness of the captured image. The summarized image processing data results for fruit visibility and recognition rate under each group and every condition can be seen in Table 6.1. The fruit visibility was computed as mentioned in experimental section while recognition rate was calculated only for the fruits which had fruit visibility above 76%. The base for recognition rate was selected as fruit visibility above 76% because after this percentage the detection was considered as possible detection range which might lead to successful detection but not always and not precise.

6.5 Results and Discussion: IR 80 Optical Filters

By using IR 80 optical filter, Figure 6.8 shows the day time and night time captured images with 3 LEDs under G4 group.

Figure 6.8: Images captured under G4 with 3 LEDs: day time (left), night time (right)

In case of IR 80 optical filter, the image processing results were also found almost same as that of IR 78 optical filter. There was no significant relation found between IR 80 optical filter and detection of sweet peppers. The detection rate was found very poor for images captured during day time. Unlike IR 78 optical filter, IR 80 optical filter showed some good recognition results when intensity of IR artificial lighting was increased but still there was only few cases in which recognition was found more than 76%. The color of fruits, leaves, stems and background was also found almost same as that of IR 78 optical filter. With no artificial light, IR 80 optical filter was found suitable for detection of soil matter effectively but when artificial lighting was used the soil matter detection rate was decreased. The fruit visibility was not found significant by using IR 80 optical filter. Figure 6.9 shows the results obtained by image processing for IR 80 optical filter in day time and night time under various conditions.

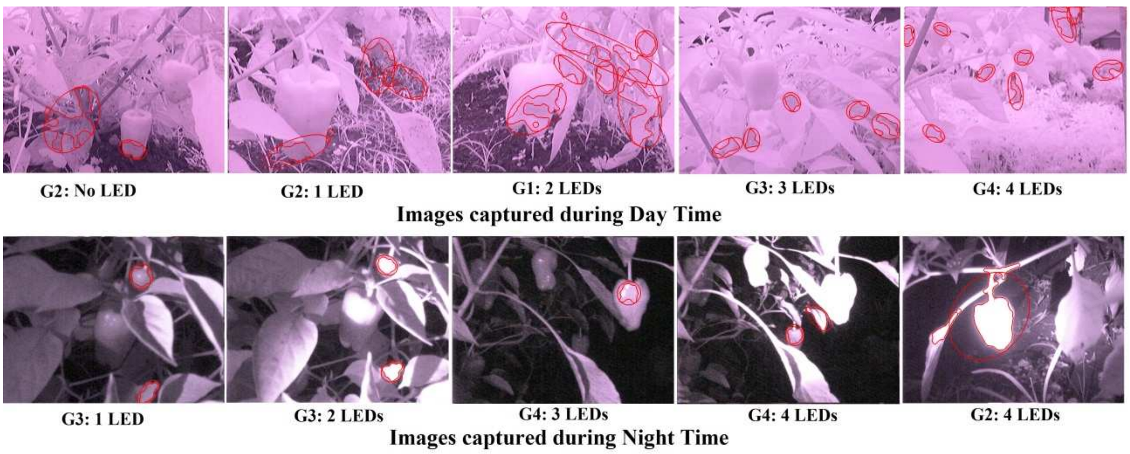


Figure 6.9: Recognition results by IR 80 optical filter

In case of images captured during night time, again the role of light intensity was found a key factor with instability and uncertainty that cased detection of fruit. At low intensity of IR artificial lighting, the fruit visibility was low but it increased with increase in intensity of artificial lighting. With 4 LEDs on, the detection rate was found satisfactory but when intensity of artificial lighting reduced, the detection was found less than 25% for same scene. When the intensity of lighting high; the detection of fruit included fruit, stem and part of leaves from the scene whose portions were exposed to the high brightness. Based on the results obtained by IR 80 optical filter, it was concluded that, the fruit detection and fruit visibility was not significant and effective and IR 80 optical filter also failed to detect the sweet peppers in natural background.

To verify the feature attribute feasibility, the histogram analysis was done on images captured during night time and results of analysis can be seen in Figure 6.10.

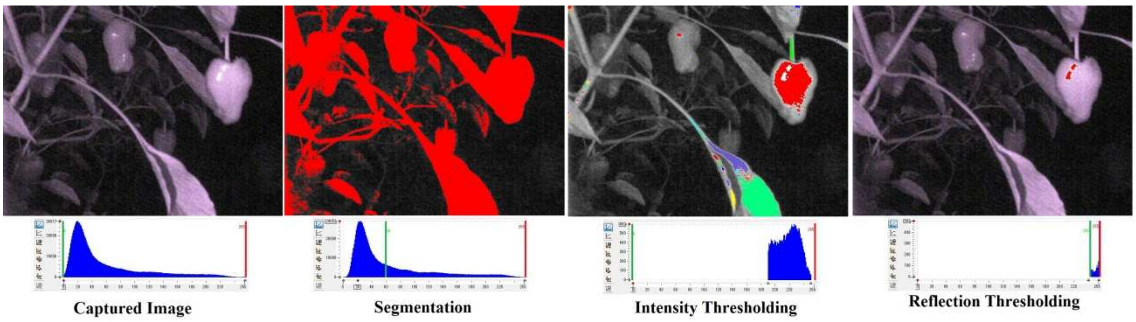


Figure 6.10: Histogram analysis for IR 80 optical filter

During the image histogram analysis, it was found that the histogram of feature attribute of fruit reflection was almost same that of histogram of intensity thresholding. In the above figure, it was clear that the after noise removal, segmentation separates the crop portion from the background but at thresholding operation was very critical. In thresholding, the specified thresholding value by algorithm includes the brightness and chroma of high light intensity and reflection from feature attribute. These two thresholding values were found very close and cannot be distinguished separately which results in low detection rate as it only focuses on the high intensity portion in the image rather reflection from the fruits.

In the Figure 6.10, the two thresholding values were separated manually to show the tiny difference in the light intensity and reflection feature from the scene. The main reason behind this might be the less reflection from the fruits or failure in comprehension of two thresholding values by algorithm. For the main fruit in the scene, the difference between two thresholding was very narrow while in case of other fruits, though there was small reflection occurred, the reflection thresholding failed to detect that reflection on other fruits and threshold as light intensity thresholding. These types of biased results create false detection of fruits and influence on the recognition rate. This clearly delivered an idea that although there was very tiny difference occurred between reflection feature and light intensity, the IR 80 optical filter failed to separate them. However, these was an interesting observation made, by using IR 80 filter, the reflection from the leaves or stem was not found during image processing which might reduce the false detection. The cases where false detection was observed as leaves that was due to the high light intensities and not by any reflection of leaves.

The summarized image processing data results for fruit visibility and recognition rate under each group and every condition can be seen in Table 6.2. Based on the histogram analysis and results obtained by image processing of IR 80 optical filter, it was concluded that the IR 80 optical filter cannot be used for detection of sweet peppers effectively as it fails to distinguish the high IR artificial lighting and feature attributes in the scene which caused due to very miniature difference between thresholding values.

6.6 Results and Discussion: IR 90 Optical Filters

By using IR 90 optical filter, Figure 6.11 shows the day time and night time captured images with 4 LEDs under G2 group.

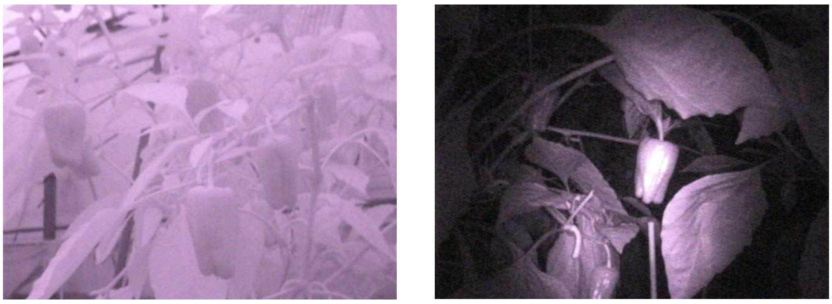


Figure 6.11: Images captured under G2 with 4 LEDs: day time (left), night time (right)

IR 90 optical filter was found significantly effective for detection of sweet peppers. There was considerable difference observed between reflection feature and light intensity. The results of image processing by IR 90 optical filter can be seen in Figure 6.12.

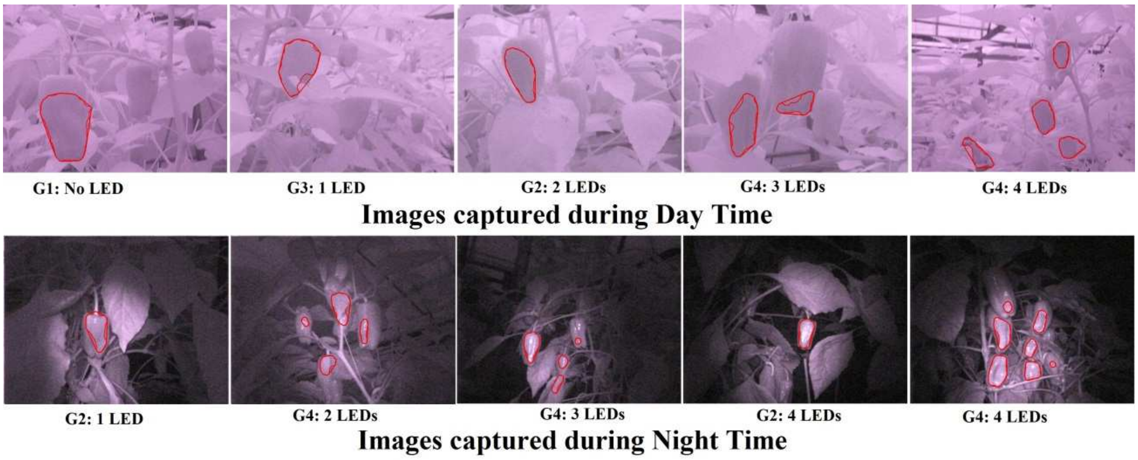


Figure 6.12: Recognition results by IR 90 optical filter

The image processing results shows that the percent detection and fruit visibility was higher than IR 78 and 80 optical filters. Also, the night time detection was found more reliable and successful compared with day time detection. The images captured during day time showed significant results but the fruit visibility was found low. For the images captured during day time, the color of fruits and color of background, leaves and stems was slightly different. This difference can be spotted easily which helps to reduce complications in segmentation and thresholding process. In the day time the effect of IR artificial lighting was not found effective on detection of sweet peppers. Increase or decrease in the light intensity could not alter the feature attributes due to the effect of sunlight. Most of the detection of sweet peppers was occurred due to the difference in the color of fruits and rest of the background.

In case of images captured during night time, the detection of fruits and fruit visibility was observed higher than that of images captured during day time. The main reason for this was not the color difference between fruits and rest of background but the feature attribute. During image processing, it was observed that the reflection from the fruits was higher while there was less or no reflection occurred from leaves or stems. The increased in the IR artificial lighting increases the reflection and also increases the light intensity but there was considerable difference between these two features. During the image processing, it was also observed that there was less influence of the IR artificial lighting on detection of fruits. Also, the reflection from the fruits was higher for high light intensity compared with reflection from the fruits with low light intensity. The light intensity with 3 and 4 LEDs had higher fruit visibility compared with 1 and 2 LEDs which confirmed the feature attribute as a key factor for successful fruit detection. The fruit visibility was higher in G1 and G2 groups while in G3 and G4 groups, the fruit visibility was higher but the detection was observed with some portions from the scene. This means the sweet peppers were detected successfully from the captured images but at the same time some part of leaves of stems or background also detected as a fruit. This was might be possible due to the slight influence of high light intensity on the fruits and segmentation and thresholding failure to distinguish this small influence during image processing. The image processing results also confirmed successful detection of multiple sweet peppers in the scene by using IR 90 optical filter. Based on the data analysis and results obtained from image processing, it was concluded that IR 90 optical filter can be used for sweet pepper detection effectively during night time with 2 – 4 LEDs combination. To avoid mismatching or false detection due to influence of light intensity, image processing algorithm needs further improvement. The summarized image processing data results for fruit visibility and recognition rate under each group and every condition can be seen in Table 6.3.

To investigate the effect of light intensity on feature attribute, image histogram analysis was done which can be seen in Figure 6.13.

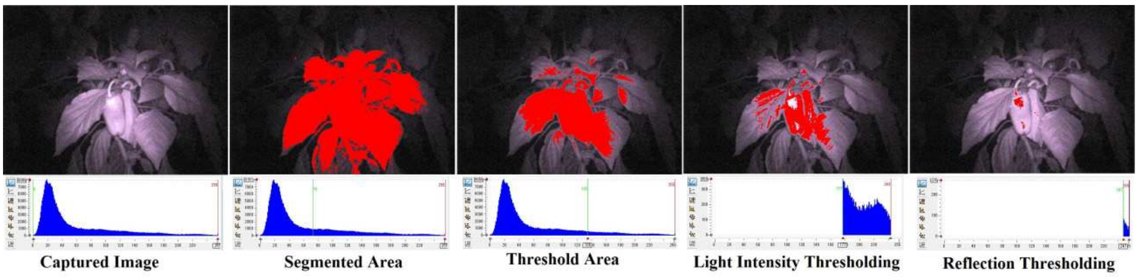


Figure 6.13: Histogram analysis for IR 90 optical filter

During the image processing, there was significant difference found between IR artificial light intensity and refection feature attribute in the scene. The histogram analysis to investigate the influence of light intensity on feature attribute provides insight onto the key factors for detection of fruit. In the thresholding, light intensity and reflection had considerable variations in thresholding values. The images influenced by intensity and had false detection; thresholding on the selected area and extracting the reflection feature thresholding values might cause the process to be critical which results in influencing detection of fruit and false detection. In IR 80 optical filter, it was observed that the thresholding values of light intensity and reflection features were almost overlapping or tiny and image processing algorithm failed to distinguish them. But in case of IR 90, there was significant difference observed in thresholding values of light intensity and reflection features from fruits. This was the main reason for successful detection and high fruit visibility in G3 and G4 groups where the situations were difficult to locate the sweet peppers.

The influence of change in camera angle to capture the image was also tested to ensure the significance of sweet pepper detection by IR 90 optical filter. The variation in the image capture angle had significant effect on the detection of fruits and fruit visibility. The same scene captured with two different angles showed different detection results with different fruit visibility percentage. Figure 6.14 shows the image capture angle variation effect on fruit detection in which same scene was captured by slightly changing capture angle. The main purpose changing capture angle was to verify that is there any influence of image capture angle on detection of fruits and not to study which angle might be better for image capturing. By changing image capture angle, it was observed that fruit detection rate changes rapidly and fruit visibility percentage also either increases or decreases depending on the lighting conditions.

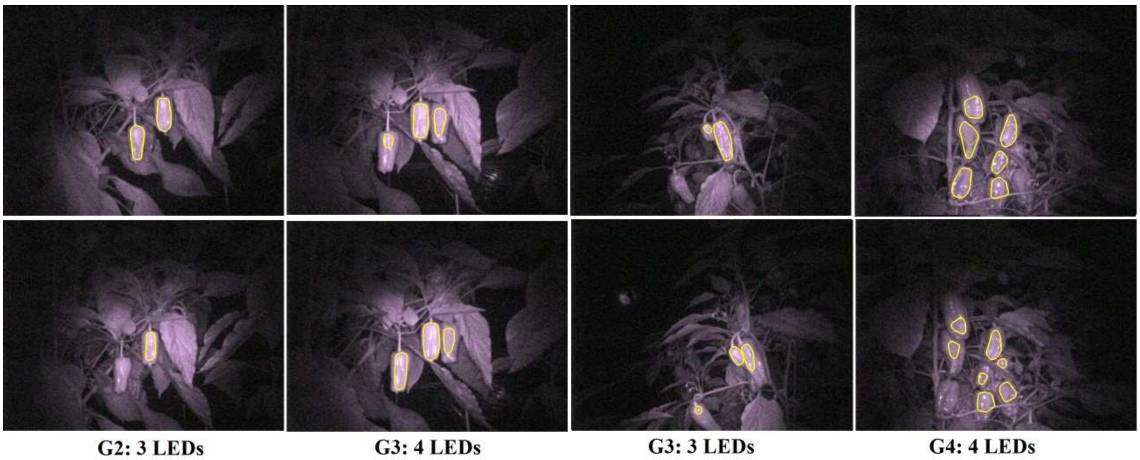


Figure 6.14: Influence of image capture angle on fruit detection

Based on the image analysis data and image processing results, it was concluded that IR 90 optical filter can be used for night time fruit detection significantly with precise care of lighting and image capture angle conditions.

6.7 Results and Discussion: IR 96 Optical Filters

By using IR 96 optical filter, Figure 6.15 shows the images captured during day time under different groups with no IR artificial lighting. Due to technical reasons and unavailability of IR LEDs of wavelength more than 960 nm for illumination, only day time images under 4 groups without using any IR artificial lighting were captured and processed for fruit detection results.

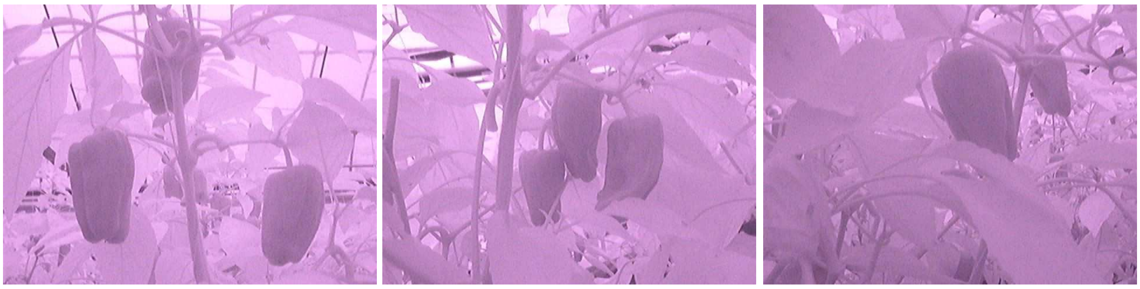


Figure 6.15: Images captured by IR 96 optical filter during day time

During the image capturing and image processing, it was observed that there was significant difference between fruits and rest of the background and this difference was higher than images captured by using IR 90 optical filter. This difference was the main key point to separate the fruits from background by using simple thresholding operation during image processing. The low pass filter helps to separate the fruits from the scene and feature attributes like area and anisometry helps to select the appropriate shape of fruits based on thresholding operation. During the image processing, it was also found that the stems and branches of plant were selected in segmentation operation but low pass filtering and feature attributes also help to deduct them in thresholding process. The small elements from the scene can be filtered easily and as there was significant difference between color of fruits and background was found, multi-detection of fruits was also possible. Unlike other optical filters, IR 96 shows significant results of multi-detection of sweet peppers in same scene. Also, the image processing results were not influenced by image capture angle as that of IR 90 optical filter.

Figure 6.16 illustrates the color difference between fruits and rest of the background under various group conditions. The captured images and color difference of fruits from background were represented with their respective histograms.

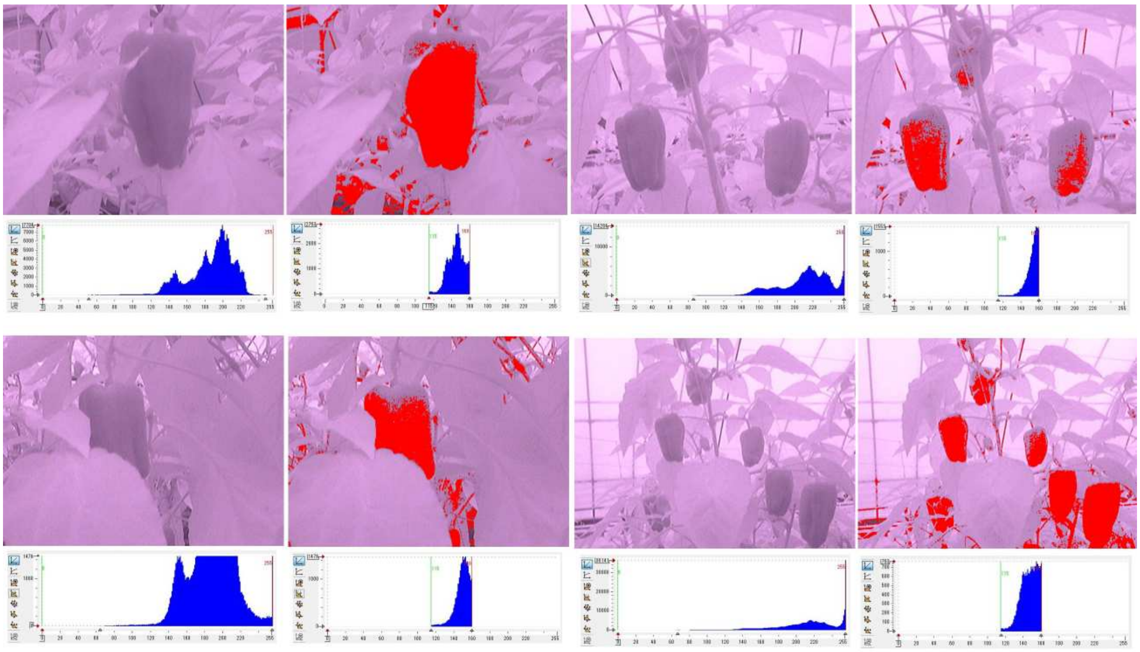


Figure 6.16: Histogram analysis for IR 96 optical filter

From the histogram analysis, it was confirmed that IR 96 optical filter can distinguish fruits from background very effectively without using any IR artificial lighting. The day time sun light influence was not found for IR 96 optical filter. The histogram analysis clearly shows that the fruit color had low gray histo values while rest of the background had high histo values. By equalizing histograms linearly, the initial noise was removed followed by segmentation and thresholding. The image processing results obtained for various group conditions with no IR artificial lighting can be seen in Figure 6.17 which clearly shows high recognition rate of fruits and high fruit visibility.

By using IR 96 optical filter the fruit detection rate was higher in all the 4 selected groups compared with all other IR optical filters. For group G1 and G2 the fruit detection rate was found very higher than group G3 and G4. Apart from selected 4 groups, IR 96 optical filter was also found very suitable and highly effective for multi-detection of sweet peppers in single captured image input. Though all the fruits were not detected but most of the fruits were detected with high fruit visibility percentage.

Specially, the occluded or fruits covered by leaves and stems or fruits covered by fruits were also found recognized by IR 96 optical filter. This clearly provides confirmation that IR 96 optical filter can be used for multi-detection of fruits, occluded or overlapped fruits very significantly and effectively with high percentage of fruit visibility. The summarized image processing data results for fruit visibility and recognition rate under each group and every condition can be seen in Table 6.4.

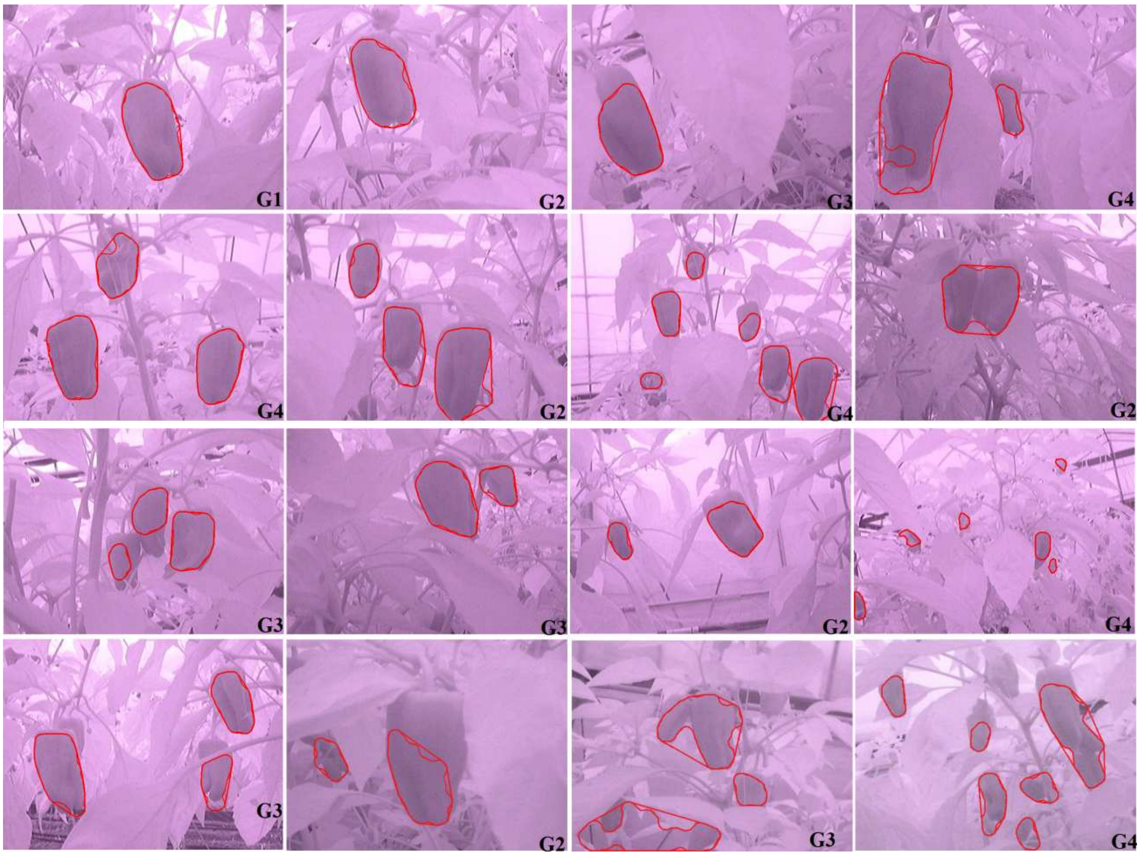


Figure 6.17: Recognition results by IR 96 optical filter

For some cases where failure in fruit detection was observed, that was due to extremely high occlusion of fruits or hard situations like fruits covered by leaves and stems more than 80%. Also, it was found that if any soil surface or black components like drip lines or greenhouse structure frames were accidently captured in the scene; then there are possibilities of false detection or mismatch detection of those components and soil surface along with sweet peppers. The reason for false or mismatch detection was the low pass thresholding filter used during image processing that matches with soil surface thresholding. So by avoiding these components during image capturing or capturing images horizontally parallel, false and mismatch detection can be reduced.

Table 6.1: Recognition results for IR 78 optical filter

<table>
<tr><th colspan="3" rowspan="2"></th><th rowspan="2">Total Images</th><th colspan="5">Detection of sweet Peppers</th><th rowspan="2">Recognition Rate, %</th></tr>
<tr><th>Failed</th><th>0-25%</th><th>26-50%</th><th>51-75%</th><th>76-100%</th></tr>
<tr><td rowspan="20">Day Time</td><td rowspan="4">No LED</td><td>G1</td><td>5</td><td>5</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>G2</td><td>5</td><td>5</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>G3</td><td>5</td><td>5</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>G4</td><td>5</td><td>5</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td rowspan="4">1 LED</td><td>G1</td><td>5</td><td>5</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>G2</td><td>5</td><td>5</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>G3</td><td>5</td><td>5</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>G4</td><td>5</td><td>5</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td rowspan="4">2 LEDs</td><td>G1</td><td>5</td><td>5</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>G2</td><td>5</td><td>5</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>G3</td><td>5</td><td>5</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>G4</td><td>5</td><td>5</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td rowspan="4">3 LEDs</td><td>G1</td><td>5</td><td>2</td><td>2</td><td>1</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>G2</td><td>5</td><td>3</td><td>2</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>G3</td><td>5</td><td>5</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>G4</td><td>5</td><td>5</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td rowspan="4">4 LEDs</td><td>G1</td><td>5</td><td>4</td><td>1</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>G2</td><td>5</td><td>5</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>G3</td><td>5</td><td>4</td><td>1</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>G4</td><td>5</td><td>5</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td rowspan="16">Night Time</td><td rowspan="4">1 LED</td><td>G1</td><td>5</td><td>4</td><td>1</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>G2</td><td>5</td><td>4</td><td>1</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>G3</td><td>5</td><td>5</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>G4</td><td>5</td><td>5</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td rowspan="4">2 LEDs</td><td>G1</td><td>5</td><td>3</td><td>2</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>G2</td><td>5</td><td>3</td><td>1</td><td>1</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>G3</td><td>5</td><td>5</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>G4</td><td>5</td><td>5</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td rowspan="4">3 LEDs</td><td>G1</td><td>5</td><td>2</td><td>3</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>G2</td><td>5</td><td>1</td><td>3</td><td>0</td><td>1</td><td>0</td><td>0</td></tr>
<tr><td>G3</td><td>5</td><td>3</td><td>2</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>G4</td><td>5</td><td>2</td><td>2</td><td>1</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td rowspan="4">4 LEDs</td><td>G1</td><td>5</td><td>1</td><td>1</td><td>0</td><td>2</td><td>1</td><td>20</td></tr>
<tr><td>G2</td><td>5</td><td>2</td><td>2</td><td>0</td><td>0</td><td>1</td><td>20</td></tr>
<tr><td>G3</td><td>5</td><td>1</td><td>1</td><td>2</td><td>0</td><td>1</td><td>20</td></tr>
<tr><td>G4</td><td>5</td><td>2</td><td>1</td><td>0</td><td>1</td><td>1</td><td>20</td></tr>
<tr><td colspan="3">Total</td><td>180</td><td>141</td><td>26</td><td>5</td><td>4</td><td>4</td><td>2.22</td></tr>
</table>

Table 6.2: Recognition results for IR 80 optical filter

			Total Images	Detection of sweet Peppers					Recognition Rate, %
				Failed	0-25%	26-50%	51-75%	76-100%	
Day Time	No LED	G1	3	2	1	0	0	0	0.00
		G2	3	2	1	0	0	0	0.00
		G3	3	3	0	0	0	0	0.00
		G4	3	3	0	0	0	0	0.00
	1 LED	G1	3	1	2	0	0	0	0.00
		G2	3	2	1	0	0	0	0.00
		G3	3	3	0	0	0	0	0.00
		G4	3	3	0	0	0	0	0.00
	2 LEDs	G1	3	1	1	1	0	0	0.00
		G2	3	2	0	1	0	0	0.00
		G3	3	2	1	0	0	0	0.00
		G4	3	3	0	0	0	0	0.00
	3 LEDs	G1	3	1	1	0	1	0	0.00
		G2	3	1	2	0	0	0	0.00
		G3	3	1	1	0	1	0	0.00
		G4	3	0	1	1	0	1	33.33
	4 LEDs	G1	3	0	2	1	0	0	0.00
		G2	3	1	1	0	0	1	33.33
		G3	3	3	0	0	0	0	0.00
		G4	3	3	0	0	0	0	0.00
Night Time	1 LED	G1	3	1	1	0	0	1	33.33
		G2	3	1	1	0	0	1	33.33
		G3	3	2	0	1	0	0	0.00
		G4	3	2	1	0	0	0	0.00
	2 LEDs	G1	3	0	3	0	0	0	0.00
		G2	3	0	1	0	1	1	33.33
		G3	3	2	0	1	0	0	0.00
		G4	3	3	0	0	0	0	0.00
	3 LEDs	G1	3	0	1	0	0	2	66.67
		G2	3	0	2	0	1	0	0.00
		G3	3	0	1	1	0	1	33.33
		G4	3	1	1	0	0	1	33.33
	4 LEDs	G1	3	0	0	1	0	2	66.67
		G2	3	1	0	1	0	1	33.33
		G3	3	0	1	0	2	0	0.00
		G4	3	1	0	1	0	1	33.33
Total			108	51	28	10	6	13	12.04

Table 6.3: Recognition results for IR 90 optical filter

			Total Images	Detection of sweet Peppers					Recognition Rate, %
				Failed	0-25%	26-50%	51-75%	76-100%	
Day Time	**No LED**	G1	15	4	3	1	3	4	26.67
		G2	15	3	6	2	2	2	13.33
		G3	15	6	3	2	1	3	20.00
		G4	15	9	2	1	1	2	13.33
	1 LED	G1	15	2	3	2	1	7	46.67
		G2	15	4	2	3	1	5	33.33
		G3	15	3	6	3	1	2	13.33
		G4	15	6	5	1	1	2	13.33
	2 LEDs	G1	15	4	2	5	0	4	26.67
		G2	15	1	2	2	3	7	46.67
		G3	15	4	1	2	1	7	46.67
		G4	15	8	4	2	0	1	6.67
	3 LEDs	G1	15	1	4	1	1	8	53.33
		G2	15	3	1	2	1	8	53.33
		G3	15	4	2	1	1	7	46.67
		G4	15	10	1	1	0	3	20.00
	4 LEDs	G1	15	1	2	1	1	10	66.67
		G2	15	3	1	1	2	8	53.33
		G3	15	7	1	2	0	5	33.33
		G4	15	8	1	1	2	3	20.00
Night Time	**1 LED**	G1	15	2	2	1	2	8	53.33
		G2	15	1	2	2	1	9	60.00
		G3	15	2	3	3	1	6	40.00
		G4	15	3	1	3	1	7	46.67
	2 LEDs	G1	15	1	0	0	1	13	86.67
		G2	15	1	1	2	1	10	66.67
		G3	15	0	3	2	1	9	60.00
		G4	15	3	3	1	2	6	40.00
	3 LEDs	G1	15	0	1	1	0	13	86.67
		G2	15	1	0	0	1	13	86.67
		G3	15	1	2	1	2	9	60.00
		G4	15	3	1	1	4	6	40.00
	4 LEDs	G1	15	0	0	0	1	14	93.33
		G2	15	0	1	1	1	12	80.00
		G3	15	1	1	1	1	11	73.33
		G4	15	1	1	0	0	13	86.67
Total			540	111	74	55	43	257	47.59

Table 6.4: Recognition results for IR 96 optical filter

			Total Images	Detection of sweet Peppers					Recognition Rate, %
				Failed	0-25%	26-50%	51-75%	76-100%	
Day Time	**No LED**	G1	128	2	2	4	3	117	91.41
		G2	87	5	3	2	4	73	83.91
		G3	81	6	3	4	7	61	75.31
		G4	94	6	1	3	6	78	82.98
Total			390	19	9	13	20	329	84.35

Based on the image data analysis and results obtained from image processing software for all IR optical filters, the summary of results can be seen in Table 6.5 which gives insight onto the detection rate, fruit visibility percentage and influencing factors on fruit detection for all IR optical filters.

Table 6.5: Summary of multispectral recognition system

Filter	Fruit detection	Fruit visibility	Influencing factors	Remarks
IR 78	Low	Low	Light intensity	- Not suitable for recognition - Day time imaging is not effective - Fruit and background color almost same - Feature attributes and light intensity thresholding values had tiny difference
IR 80	Low	Low	Light intensity	
IR 90	High	High	Image capture angle and distance	- Moderately suitable for recognition with precise care of light intensity and image capture angle - Night time imaging very effective - Significant difference between color of fruit and background
IR 96	Very high	Very high	Soil surface and structure components of greenhouse	- Avoid soil surface and greenhouse structure components in scene - Day time imaging is very effective without any IR artificial lighting - Fruit color found completely different than background color in day time - Multi-detection in single scene is possible - Occluded and overlapped fruits can be detected significantly

6.8 Sweet Pepper Maturity Determination

Multispectral imaging is a technology originally developed for space-based imaging which may capture light from wavelengths beyond the visible light range, such as infrared, allowing the extraction of additional information that the human eye fails to capture. Multispectral imaging can be used to address the external features such as ripening [6.20] and external defects [6.21 – 6.25] with higher sensitivity in comparison to the ordinary RGB imaging [6.26 – 6.27]. By considering these previous research work, it was decided that to investigate the maturity detection by using multispectral recognition system for sweet peppers. As IR 96 optical filter showed significant results for detection of sweet peppers, hence by using same optical filter, the possibilities of fruit maturity detection was carried out. To investigate the maturity detection possibilities, it was important to find out the strong correlation factor between optical filter wavelength and maturity of sweet peppers.

Chlorophylls are the most important pigments for photosynthesis and the green color of sweet peppers and leaves. The chlorophyll content in sweet peppers start to increase with growth of the fruit and it is maximum when fruits are at early maturity stage [6.28-6.29]. The chlorophylls have strong reflectance peaks in the red and blue wavelength regions. Blue peak cannot be used to estimate the chlorophyll content because it overlaps with the absorbance of the carotenoids. Maximal absorbance in the red region occurs between 660 nm and 680 nm. However, it is unknown if reflectance at these wavelengths can be used to predict chlorophyll content as reflectance at slightly longer or shorter wavelengths. This is because absorption in the 660– 680 nm tends to saturate at low chlorophyll content, thus reducing the sensitivity of the spectral indices based on these wavelength to high chlorophyll content [6.30]. Empirical models to predict chlorophyll content are largely based on reflectance around the 550 nm or 1060 nm regions where the absorption is saturated at higher chlorophyll. Indices formulated with these bands would thus have higher accuracy in estimating chlorophyll content.

Thus, based on chlorophyll content correlation, the maturity determination possibilities were tested for sweet peppers. There were two main concerns during testing these possibilities by image processing:

1. The chlorophyll presents in fruits and in leaves as well; this might increase the complication in image processing and results in false conclusions. Hence, it was decided that the detection of fruits must be obtained first by image processing and then the maturity determination can be tested for detected fruits only.
2. The images were captured using IR optical filter and as mentioned above, the chlorophyll content saturation reflectance highly related in red wavelength. So overcome this problem, an effective algorithm which can transform the multispectral images into red wavelength band was required. By using the principle component analysis this problem was solved.

Figure 6.18 illustrates the algorithm used for fruit detection and maturity detection of sweet peppers. The fruit detection algorithm was the same algorithm used before as presented in Figure 6.2.

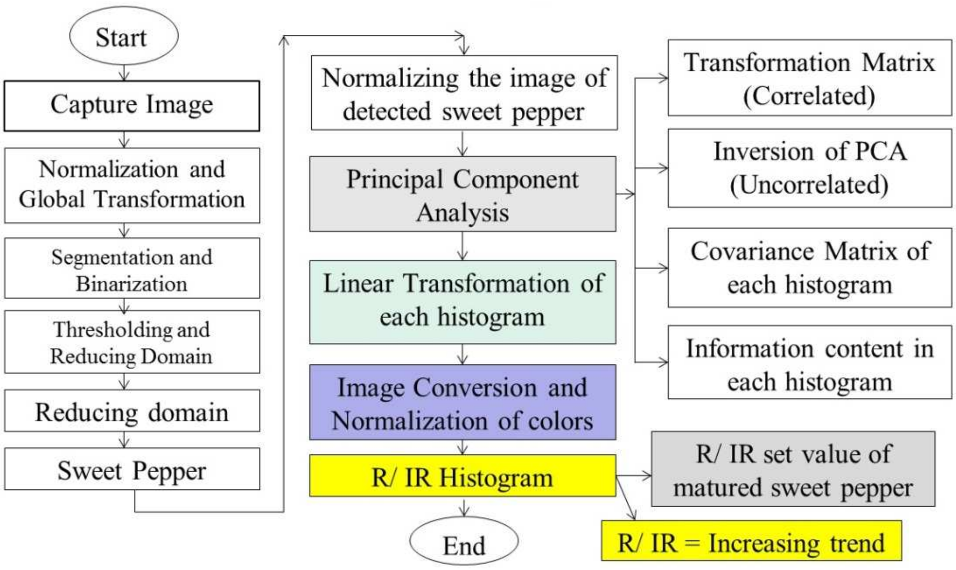


Figure 6.18: Fruit detection and maturity determination algorithm

After the successful detection of sweet peppers in the scene, the detected fruit area was selected manually to continue with maturity detection algorithm. The selected input image area was normalized to remove small noise if any followed by Principle Component Analysis (PCA). In PCA, 4 important operations were carried out – pixel wise correlated transformation matrix was obtained for each channel; the obtained correlated channel was inverted for each channel which results in uncorrelated matrix (the spectral bands are highly correlated; it is desirable to transform them to uncorrelated images. This can be helpful for discarding the bands containing little information and with respect to a later classification step); the covariance matrix for each histogram was obtained by computing the mean gray value of the channels and the n × n covariance matrix of the channels; finally, the results provides the relative information in each channel and can be analyzed by using histograms. After PCA, the histograms obtained in each channel were normalized for colors. Finally, the decision step was introduced which uses R/ IR histogram ratio to determine the maturity stage of input detected sweet pepper. At this decision making step, the decision can be set by two ways: by observing the trend of R/IR histogram ratio or providing pre-set histogram values of matured sweet peppers. In case of R/ IR histogram ratio, the trend should be increasing for maturity of fruits. To visualize this trend, the final histograms were obtained in which the histogram with green color represents the matured fruit and green histogram with other histograms or absence of green histogram represents not matured fruits.

The R/ IR histogram ratios were computed based on the transformed chlorophyll adsorption ratio index and defined as follows:

$$\frac{R}{IR}\,[680,\ 960] = 3\left[(R_{960} - R_{680}) - 0.2(R_{960} - R_{550})\left(\frac{R_{960}}{R_{680}}\right)\right] \qquad (6.3)$$

Where,

R_{960}	=	IR 96 optical filter histogram
R_{680}	=	histogram value of red channel for peak reflectance of chlorophyll
R_{550}	=	histogram value of green channel

Based on the fruit detection and maturity determination algorithm mentioned above, the images were processed accordingly and obtained results can be seen in Figure 6.19. In the results, as mentioned before, the green histograms represent the detected matured fruits while other color histograms represents detected but not matured fruits. To verify the results obtained, the tests were conducted on the fruits whose maturity can be stated by observation such as 2L size sweet peppers and small sweet peppers. The pre-know maturity status fruits were processed by algorithm mentioned above and results were verified.

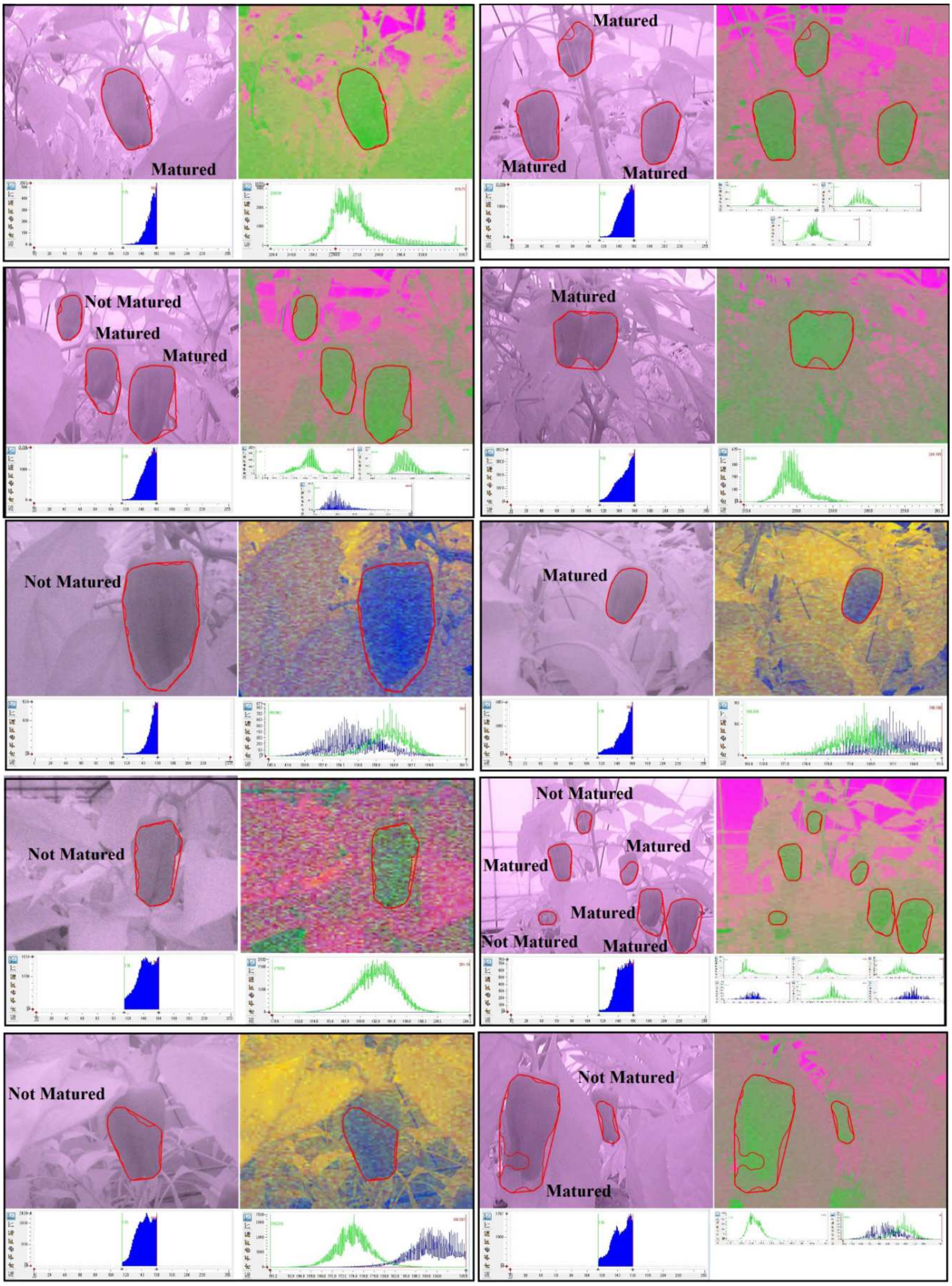


Figure 6.19: Maturity determination results for detected sweet peppers

(First image shows pre-known status of detected fruits while second image shows result image with histograms for maturity determination: green color – matured; other colors – not matured)

During the analysis of results obtained for fruit maturity detection, it was found that the algorithm developed for fruit maturity detection provides satisfactory results but in some cases the results were unstable. As the fruit detection was possible by using IR 96 optical filter, the detected fruit area input image provides significant results of fruit maturity detection in some cases but same time there were some false results obtained. The pre-known samples were tested for maturity detection and it was found that in some cases though the samples were matured, the maturity detection results were opposite or if samples were not matured, the maturity detection results were false. On the other hand, it was also found that in many cases the maturity detection results obtained were perfect. The reason for unstable maturity detection results was probably due to the PCA analysis or image processing algorithm which might failed to correlate the chlorophyll content effectively with R/ IR histogram ratio. But based on the accurate results for maturity detection, the algorithm controversially provides significant results which mean the PCA analysis and algorithm might need further improvements.

Based in the results obtained for fruit maturity detection it was concluded that the maturity detection was possible by using IR 96 optical filter though there were some false results obtained. By improving the PCA analysis and image processing algorithm, the false results could be avoided. The summarized data on maturity detection with different groups by using IR 96 optical filter can be seen in Table 6.6. The images used for maturity detection were the images which had fruit visibility more than 76%.

Table 6.6: Fruit maturity determination results

	No. of images	Fruit detected images	True Results	False Results	Failed to determine maturity	Maturity detection, %	Maturity detection failure, %
G1	128	117	89	17	11	76.07	23.93
G2	87	73	43	21	9	58.90	41.10
G3	81	61	27	14	20	44.26	55.74
G4	94	78	32	29	17	41.03	58.97
Total	390	329	191	81	57	58.05	41.95

The maturity determination was found high in G1 group followed by decreasing trend for other groups. For difficult situations as in G3 and G4 groups, if the detection of sweet peppers was clustered or includes some portion from the scene then the maturity determination decision was taken for those combined detected areas which might be not accurate and hence decreasing the maturity determination percentage. For these groups, when leaves or stems overlaps or occlude the fruits and detected in recognition results as a part of detected fruits; then the chlorophyll reflectance from the leaves and stems could influence the maturity determination decision. Though the fruit maturity determination results were found unstable in some cases, by improving the maturity determination algorithm and capturing the images with different camera angles and poses, the maturity determination percentage can be increased significantly. Based on the results obtained, it was concluded that IR 96 optical filter can be used significantly for fruit detection and in simple conditions; fruit maturity determination was possible which was based on strong correlation of IR wavelength to chlorophyll reflectance from fruits.

6.9 Conclusions

By considering the applications of IR and NIR in fruits based on quantitative and qualitative measures, a non-destructive multispectral recognition system was developed and tested for recognition of sweet peppers. In the multispectral IR system, 4 types of IR optical filters were used in experimentation: IR 78, IR 80, IR 90 and IR 96. For each IR optical filter, images were captured during day time with 5 artificial IR lighting conditions and night time with 4 artificial lighting conditions. The captured images were sorted in 4 different groups based on the scene complication and processed in image processing software to get the fruit detection results. After finding out the most significant and effective filter for fruit detection, the detected fruits further processed to investigate the maturity determination based on correlation of IR wavelength and chlorophyll reflectance.

For IR 78 optical filter; in case of images captured during day time, it was found that, artificial IR light does not had any effect on detection, rather there was no feature attributes occurred which could be used as asset for detection of fruits such as reflection from fruit surface or color variation in fruits and leaves. In all selected conditions, the multispectral system was not found effective to detect the sweet peppers during day time. In case of images captured during night time, it was observed that, the artificial lighting had significant influence on the detection. In some cases, the detection was possible but the percentage of false detection or no detection was higher. For detected images, after image data analysis, it was found that the detection was due to only high brightness and chroma components received from artificial lighting. The detection was not possible due to any feature attribute, rather when the artificial light intensity reduce, the same images failed to detect the fruits. In histogram analysis, no feature attribute feasibility observed for detection of fruits during image processing. In some cases where detection was possible, that was due to the high intensities of light used during image capture. The results only help to decide whether image was darker or brighter in nature when captured. The algorithm cannot distinguish the feature attributes and hence overall recognition rate and fruit visibility percentage was found very low for IR 78 optical filter. The IR 78 optical filter cannot be used for sweet pepper detection in day time or night time.

In case of IR 80 optical filter; the results obtained showed similar characteristics as that of IR 78 optical filter. The color of fruits, leaves, stems and background was also found almost same as that of IR 78 optical filter. Instead of fruit detection, with no artificial lighting, IR 80 optical filter was found suitable for detection of soil matter effectively but when artificial lighting was used the soil matter detection rate was decreased. In case of images captured during night time, again the role of light intensity was found a key factor with instability and uncertainty that cased detection of fruit. At low intensity of IR artificial lighting, the fruit visibility was low but it increased with increase in intensity of artificial lighting. When the intensity of lighting high; the detection of fruit included fruit, stem and part of leaves from the scene whose portions were exposed to the high brightness. During the image histogram analysis, it was found that the histogram of feature attribute fruit reflection was almost same that of histogram of intensity thresholding. The fruit detection thresholding and light intensity thresholding values were found very close and cannot be distinguished separately which results in low detection rate as it only focuses on the high intensity portion in the image rather reflection from the fruits. The overall fruit detection rate and fruit visibility percentage was found low by using IR 80 optical filter. The IR 80 optical filter cannot be used for detection of sweet peppers effectively as it fails to distinguish the high IR artificial lighting intensities and feature attributes in the scene which caused due to very miniature difference between thresholding values.

IR 90 optical filter was found significantly effective for detection of sweet peppers due to considerable difference between reflection feature and light intensity. For the images captured during day time, the color of fruits and color of background, leaves and stems was slightly different which helps to locate the fruits easily. Increase or decrease in the light intensity could not alter the feature attributes due to the effect of sunlight. The images captured during day time showed significant results but the fruit visibility was found low. In case of images captured during night time, the detection of fruits and fruit visibility was observed higher than that of images captured during day time. During image processing, it was observed that the reflection from the fruits was higher while there was less or no reflection occurred from leaves or stems. The increased IR artificial lighting increases the reflection and also increases the light intensity but there was considerable difference found between light intensity and feature attributes thresholding values. It was also found that the variation in the image capture angle had significant effect on the detection of fruits and fruit visibility. By changing image capture angle, it was observed that fruit detection rate changes rapidly and fruit visibility percentage also either increases or decreases depending on the lighting conditions. The IR 90 optical filter can be used significantly for night time fruit detection with precise care of lighting and image capture angle conditions as these two factors might influence the fruit detection and fruit visibility percentage.

For IR 96 optical filter, there was significant difference observed between fruits and rest of background which was main key point to discriminate the fruits from background by using low pass filter thresholding during day time. The histogram analysis confirmed that the IR 96 optical filter can distinguish fruits from background very effectively without using any IR artificial lighting or without influence of day time sun light. Further, the histogram analysis clearly shows that the fruit color had low gray histo values while rest of the background had high histo values. By using IR 96 optical filter the fruit detection rate and fruit visibility percentage was higher in all selected groups compared with all other IR optical filters. Apart from selected 4 groups, IR 96 optical filter was also found very suitable and highly effective for multi-detection of sweet peppers in single captured image input. Also, it was found that if any soil surface or black components like drip lines or greenhouse structure frames were accidently captured in the scene; then there were possibilities of false detection or mismatch detection of those components and soil surface along with sweet peppers. The IR 96 optical filter can be used for multi-detection of fruits, occluded or overlapped fruits very significantly and effectively with high percentage of fruit visibility.

The possibilities of maturity determination of detected sweet peppers were investigated by correlating the chlorophyll reflectance of the fruits with IR wavelength. It was found that the fruit maturity determination was possible by using IR 96 optical filter and correlating the wavelength with chlorophyll reflectance. The maturity determination was found high in G1 group (76.06%) and G2 group (58.90%) followed by decreasing trend for G3 and G4 groups. The single fruits or fruits with leaves whose detection was possible successfully, the maturity determination percentage was found higher compared with occluded and overlapped fruits. When leaves or stems overlaps or occlude with the fruits and detected in recognition results as a part of detected fruits; then the chlorophyll reflectance from the leaves and stems could influence the maturity determination decision. Though the fruit maturity determination results were found unstable in some cases, by improving the maturity determination algorithm and capturing the images with different camera angles and poses, the maturity determination percentage can be increased significantly.

For IR 96 optical filter, improving fruit detection algorithm based on different feature attributes, computing the 3D coordinate location of recognized fruits as described in Chapter 6 for color recognition system, improving the fruit maturity determination algorithm and PCA analysis to avoid the false or mismatch results can be considered as further research. Furthermore, investigating the sweet pepper detection and maturity determination by using IR optical filter having wavelength more than 960 nm and using other non-destructive characteristics that has strong quantitative or qualitative correlation with IR wavelengths can be considered as recommendations for future research.

Chapter VII

OVERALL CONCLUSIONS

8. Overall Conclusions

This chapter gives insight onto overall conclusions for picking systems, color recognition system and multispectral recognition system together. For detailed conclusions of each system, the conclusions section under each chapter can be referred. The recommendations for future work are given at the end of conclusions section in every chapter to improve or enhance the results.

a) Picking System – I

1. Picking system design parameter considerations and interaction factors relevant to optimal design were analyzed.
2. The conceptual design of picking system based on contact gripping strategy, operational control systems to control the movement of working components were designed successfully.
3. The optimal model of the picking system developed, simulated for its static and dynamic characteristics based on several design studies which helped to determine the materials and component structure of the picking system.
4. The prototype was developed based on obtained simulation results and validated and evaluated for its performance efficiency under various conditions.
5. The prototype showed significant results under selected testing conditions with 97.91% performance efficiency, 1.1s to perform the harvesting operation and no physical damage was observed to the harvested fruits.

b) Picking System – II

1. Considering the fruit shelf life and quality measures, thermal cutting system prototypes were developed based on amplified voltage and current potential.
2. In electric arc thermal cutting system, 1mm and 2mm diameter electrodes were tested for harvesting operation in which 1mm diameter electrodes found significant for cutting fruit stem of 5mm diameter in 2.2s.
3. In temperature arc thermal cutting system, 0.02mm, 0.5mm and 1mm diameter nichrome wire were tested for harvesting operation in which 0.5mm and 1mm

diameter nichrome wires found significantly effective for cutting fruit stem of 5mm diameter in 1.5s and 1.4s respectively.

4. Among the two prototypes, temperature arc thermal cutting system demonstrated good results in which based on physical configuration of prototype, 0.5mm diameter nichrome wire was recommended for harvesting operation.
5. By adopting thermal cutting system, the physical damage to fruits could be avoided and there was no viral or fungal transformation occurred within the harvested fruits which considerably help to preserve the quality and shelf life of fruits up to 15 days at normal room conditions.

c) Recognition System – I

1. A color recognition system and fruit detection algorithm was developed and tested for several color space models based on color making attributes and reflection feature attributes to find out the significant color space model for detection of green sweet peppers in natural background.
2. In case of color images, *HSV* color space model was found more significant with high percentage of green sweet pepper detection followed by *HSI* as both provides information in terms of hue/lightness/chroma or hue/lightness/saturation which are often more relevant to discriminate the fruit from image at specific thresholding value.
3. In *HSV* color space model, based on image histogram analysis, it was found that there was significant difference between reflection from fruits an reflection from leaves and stems. Due to this higher reflection feature attribute, the fruit visibility was higher in *HSV* color space model followed by *HSI* color space model when compared with other color space models which reduce the fruit visibility due to inconsistent or lack of reflection feature attributes.
4. The recognition rate was found higher for *HSV* color space model as 84% while for *HSI* as 72% which was further categorized into 4 different groups based on various conditions that occurs during harvesting process.
5. A color recognition system was able to recognize and locate the fruits under conditions like: single fruit, fruits with leaves, fruits with leaves and stem.

6. A color recognition system was also able to locate the fruits in the situations where certain areas of the fruits were not visible due to partial occlusion by leaves or by overlapping fruits.
7. Location and orientation i.e. 3D coordinates and inclination angle of detected fruit stem with respect to vertical axis were obtained. This positional information of detected green sweet peppers was found highly reliable in which the depth accuracy errors and disparity parallax errors were minimum when distance between cameras and fruit was 500 to 600 mm and distance between two cameras maintained to 100 mm.
8. The orientation and stem height of detected fruit was computed successfully which helps to decide the grasping and cutting points during the picking operation.
9. The developed fruit recognition algorithm was robust enough for operating in the presence of difficult and variable field condition environment like bright light reflections, shadows, variable lighting conditions, night operations and noisy background. The developed algorithm was able to operate in real-time in a general purpose sequential processor with the support of special image processing boards.

d) Recognition System – II

1. A multispectral IR recognition system and fruit detection algorithm was developed and tested during day and night time under several selected conditions in which IR 96 optical filter found significant to detect the sweet peppers in day time without any artificial IR lighting.
2. IR 78 and IR 80 optical filters were found not significant to locate the fruits as these filters were highly sensible to artificial IR lighting intensity in the night time and it was also found that there was no color difference observed between fruits and background in the day time.
3. IR 90 optical filter was found moderately suitable with reasonable fruit visibility percentage for detection of fruits in night time at high light intensities but the results were unstable as the change in image capture camera angle and distance to fruits influences the detection results. The histogram values of reflection feature attribute thresholding and light intensity thresholding had significant difference

which made sweet pepper detection possible in night time based on reflection feature attribute. There was considerable difference found between color of fruits and rest of background which caused a partial detection of fruits with IR 90 in day time.

4. IR 96 optical filter was found highly significant for fruit detection or multi-detection with high percentage of fruit visibility under several conditions during day time. There was significant color difference observed between fruits and rest of background which caused successful fruit detection and high fruit visibility percentage for single fruits, fruits with leaves or overlapped and occluded fruits by using low pass filter thresholding.
5. The fruit maturity detection algorithm was developed by using PCA analysis based on strong correlation of chlorophyll reflectance of fruits detected by IR 96 optical filter to IR wavelength. The single fruits or fruits with leaves whose detection was possible successfully, the maturity determination percentage was found higher compared with occluded and overlapped fruits.
6. The maturity determination by using developed algorithm was found high in G1 group (76.07%) and G2 group (58.90%) followed by decreasing trend for G3 and G4 groups. Unstable results were found when leaves or stems overlapped or occlude with the fruits and detected in recognition results as a part of detected fruits because the chlorophyll reflectance from the leaves and stems influences the maturity determination decision.

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APPENDICES

APPENDIX- A

Formulating Gripper Selection Steps

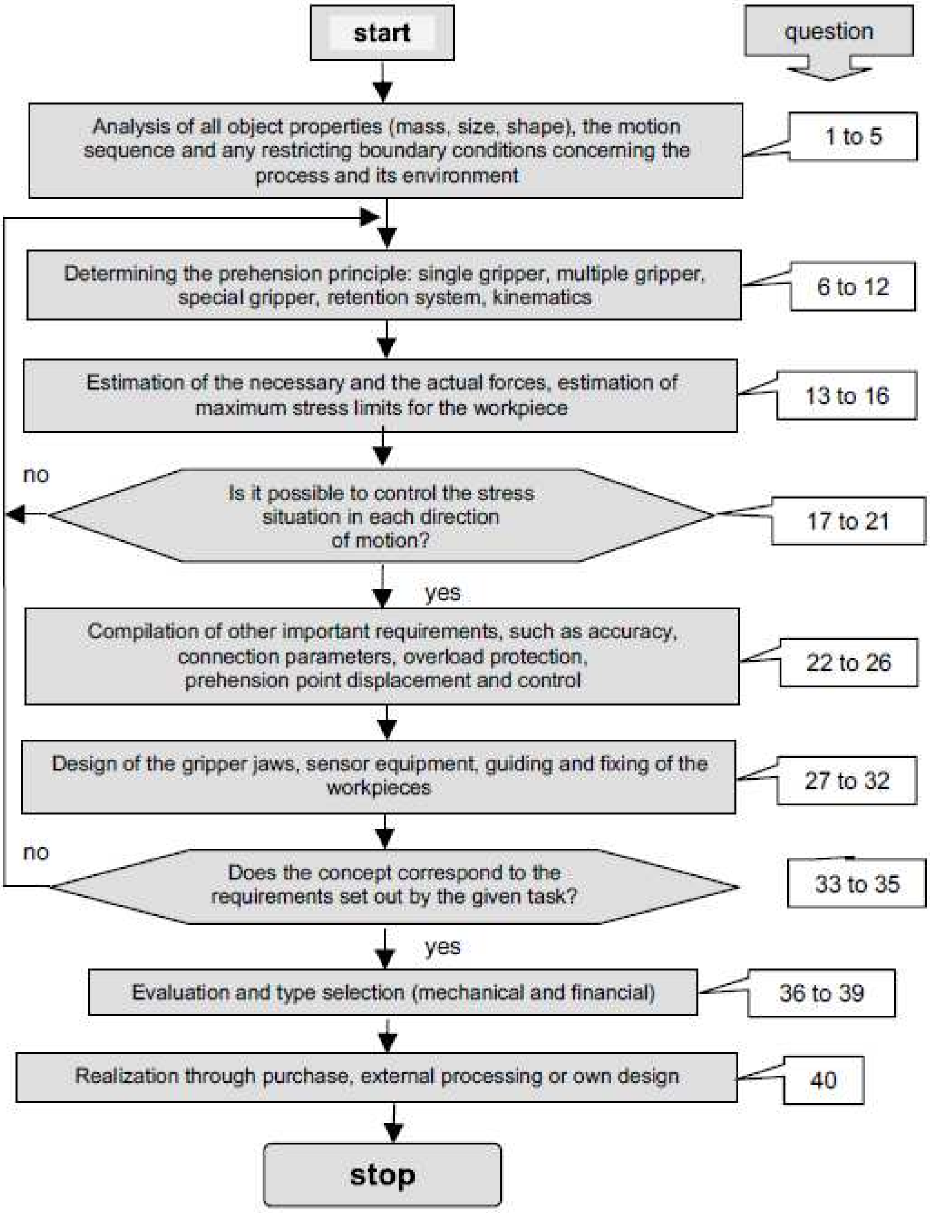

Figure A.1: Gripper selection flowchart

Questions:

1. Are the object properties, especially the mass, size, material, fragility and surface quality sufficiently known?
2. Is physical access to the object possible?
3. Is the prehension task completely defined with all necessary details? Are the initial and final spatial positions of the object defined?

4. Should the raw and finished part geometries (shape modification as a result of the operation) be accomplished by a single gripper?
5. Are all working conditions (force, pressure, temperature, object status, cycle time, friction coefficient, mass, motions, etc.) known?
6. Should the object be held by force and/ or shape matching?
7. Should one use an impactive or an astrictive principle?
8. Are the prehension surfaces given?
9. Will the work piece be held at, or in the vicinity, of its mass center of gravity?
10. Does it make a sense to use a gripper exchange system for the handling of several different components?
11. Is it planned to have shape matching in the direction of the largest acceleration component?
12. Does the retention situation in the magazine correspond to the application situation in the machine?
13. Should process forces be taken into account?
14. Is it reasonable to consider friction enhancing overlays for the gripper jaws?
15. Are the gripper and manipulator designed for the largest possible forces and moments? Is the gripper insensitive to impacts and vibration?
16. Will the work piece bear the exerted surface pressure?
17. Will the gripper sustain emergency switch-off at high velocities?
18. Has a safety factor been taken into account when dimensioning the gripper?
19. Should the prehension force be reduced in order to protect the work piece?
20. Is it necessary to secure the prehension force?
21. Does it make a sense to include collision and overload protection?
22. Does the achievable gripper accuracy satisfy the requirements?
23. Does the potentially interfering contour of the opened pose a collision danger with the surroundings?
24. What effects on the object centration can be expected from the gripper?
25. Which activation approaches can be recommended to the user?
26. Is sensory prehension verification necessary (check of object presence)?
27. Are the gripper fingers as short as possible?
28. Should the finger position be controlled by sensors?
29. Should it be recommended to switch in some joining mechanism and/ or force sensors, during assembling operation?

30. Is it planned to have several gripper jaw applications (rapid replacement)?
31. Will it be necessary to insert adaptor flanges for mounting? Are practicable mechanical, fluidic and electrical interfaces available?
32. Should the gripper jaws compensate for non-parallel object surface?
33. Is the achievable processing time acceptable? Do the opening and closing times satisfy the requirements? Are these times increased when the gripper fingers or jaws are installed?
34. What is the likely mean time between failures?
35. Are any upper limits for maximum load exceeded?
36. Is it possible to use a standard gripper or is it necessary to employ a special solution?
37. What is an acceptable operation time?
38. Which warranty regulations are applicable?
39. Should it be planned to include auxiliary equipment?
40. Is the gripper selection completer or is expert advice necessary?

APPENDIX- B

Inverter Circuit Diagram: amplifying 12V DC to 300V AC for EATCS

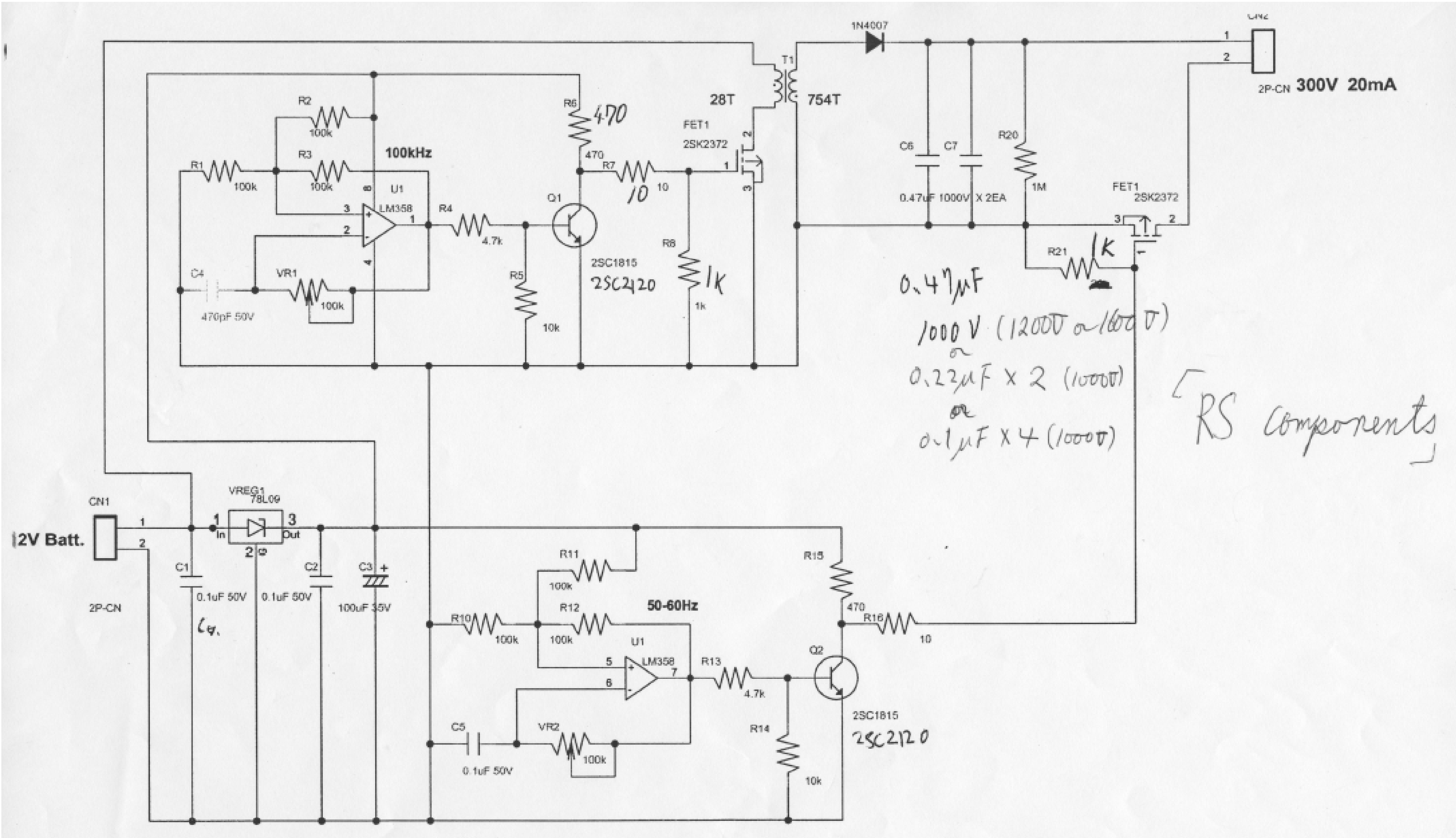

Figure B.1: Inverter circuit diagram

APPENDIX- C

Technical Drawings: Robot Manipulator Design

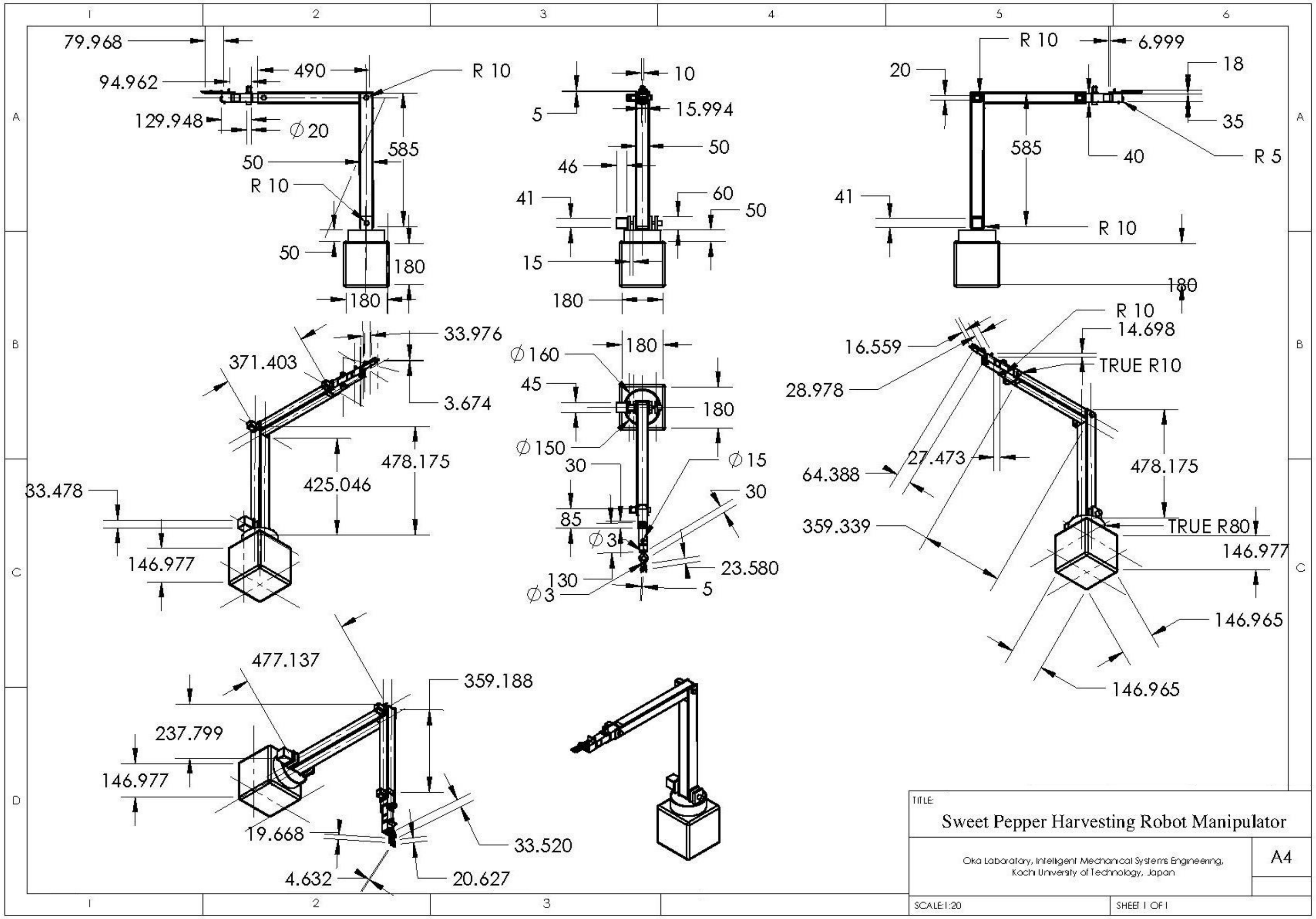

Figure C.1: Sweet pepper harvesting robot manipulator design

Technical Drawings: Picking System – I

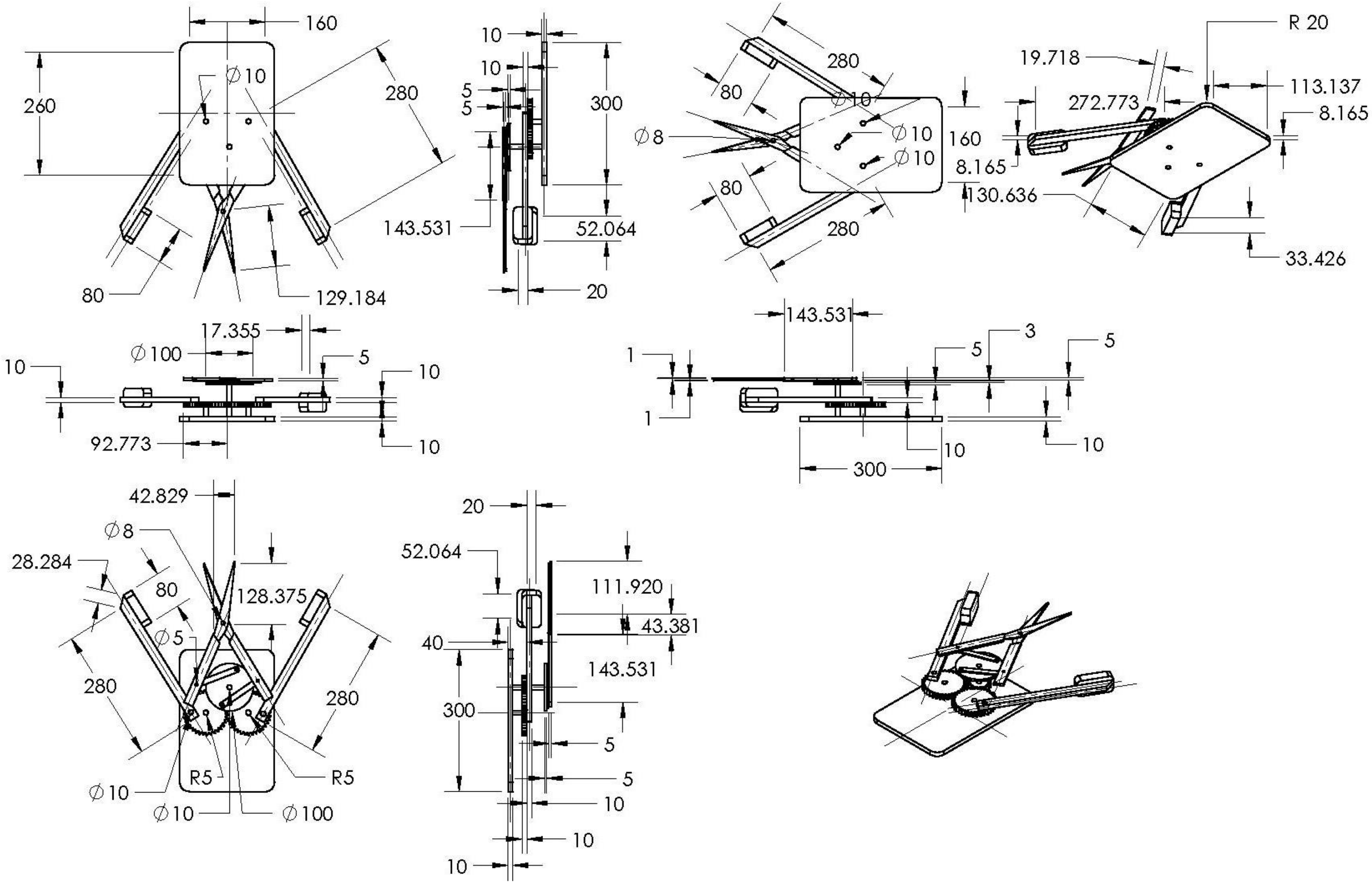

Figure C.2: Picking System – I technical drawing

Technical Drawings: Picking System – II

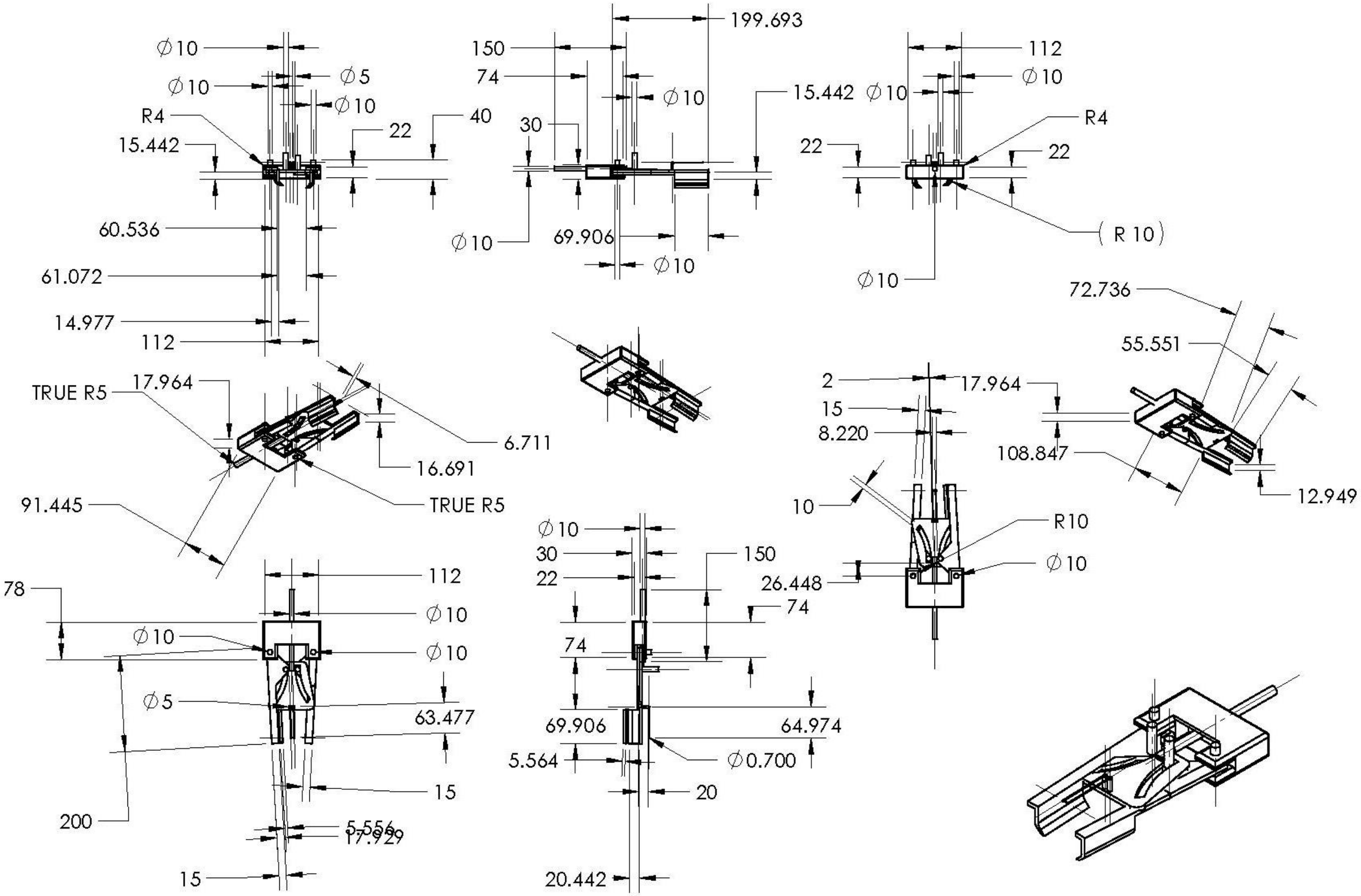

Figure C.3: Picking System – II technical drawing

APPENDIX- D

Picking System – I: System Operation Control Source Code

```
/*************************************************************************/
/*                                                                       */
/*  FILE              :KRS_CONTROL.c                                     */
/*  DATE              :Mon, Dec. 27, 2010                                */
/*  DESCRIPTION       :main program file.                                */
/*  CPU GROUP         :26                                                */
/*                                                                       */
/*************************************************************************/
#include <com.h>
#include <sio.h>
#include <led.h>
#define KRS_ID1  1
#define KRS_ID2  2
#define KRS_ID3  3
#define KRS_ID4  4
#define KRS_ID5  5
#define KRS_ID6  6
void main(void)
{
        unsigned int pos1 = 7000;
        unsigned int pos2 = 7000;
        unsigned int pos3 = 7100;
        unsigned int pos4 = 7400;
        unsigned int pos5 = 8000;
        unsigned int pos6 = 8000;
        unsigned int speed = 15;
        unsigned int stretch = 50;
        unsigned int z = 0;
        unsigned int a = 100;
        unsigned int b = 100;
        signed   int x = 0;
        cpu_init ();
        cpu_int_set ();
        ledgrn_on ();
        com_open (BR19200, 8, 1, PARITY_EVEN);
        sio1_init ();
                sio1_set_speed (1, speed);
                sio1_set_stretch (1, stretch);
                sio1_set_pos (1,4000);
        wait (7000000);
                sio1_set_speed (1,15);
                sio1_set_stretch (1, 50);
                sio1_set_pos (1,8000);
        wait (6000000);
                sio1_set_pos (KRS_ID2, pos2);
        wait (300);
                sio1_set_speed (KRS_ID2, speed);
        wait (300);
                sio1_set_stretch (KRS_ID2, stretch);
        wait (300);
```

```
            com_echo_on ();
            sio1_set_pos (KRS_ID3, pos3);
      wait (300);
            sio1_set_speed (KRS_ID3, speed);
      wait (300);
            sio1_set_stretch (KRS_ID3, stretch);
      wait (300);
            sio1_set_pos (KRS_ID4, pos4);
      wait (300);
            sio1_set_speed (KRS_ID4, speed);
      wait (300);
            sio1_set_stretch (KRS_ID4, stretch);
      wait (300);
            sio1_set_pos (KRS_ID5, pos5);
      wait (300);
            sio1_set_speed (KRS_ID5, speed);
      wait (300);
            sio1_set_stretch (KRS_ID5, stretch);
      wait (300);
            sio1_set_pos (KRS_ID6, pos6);
      wait (300);
            sio1_set_speed (KRS_ID6, speed);
      wait (300);
            sio1_set_stretch (KRS_ID6, stretch);
      wait (300);
}
```

APPENDIX- E

Picking System – II: System Operation Control Source Code

```
/**************************************************************************/
/*                                                                        */
/*  FILE            :KRS_CONTROL.c                                        */
/*  DATE            : Thu, Aug 25, 2011                                   */
/*  DESCRIPTION     :main program file.                                   */
/*  CPU GROUP       :26                                                   */
/*                                                                        */
/**************************************************************************/
#include <com.h>
#include <sio.h>
#include <led.h>
#define KRS_ID1  1
#define KRS_ID2  2
#define KRS_ID3  3
#define KRS_ID4  4
#define KRS_ID5  5
#define KRS_ID6  6
void main(void)
{
        unsigned int pos1 = 7000;
        unsigned int pos2 = 7000;
        unsigned int pos3 = 7100;
        unsigned int pos4 = 7400;
        unsigned int pos5 = 8000;
        unsigned int pos6 = 8000;
        unsigned int speed = 50;
        unsigned int stretch = 50;
        unsigned int z = 0;
        unsigned int a = 100;
        unsigned int b = 100;
        signed   int x = 0;
        cpu_init ();
        cpu_int_set ();
        ledgrn_on ();
        com_open (BR19200, 8, 1, PARITY_EVEN);
        sio1_init ();
        sio1_set_speed (1, speed);
        sio1_set_stretch (1, stretch);
        sio1_set_pos (1,9000);
        wait (3000000);
        sio1_set_speed (1,15);
        sio1_set_stretch (1, 127);
        sio1_set_pos (1,9800);
        wait (2500000);
        sio1_set_speed (1,127);
        sio1_set_stretch (1, 127);
        sio1_set_pos (1,10200);
        wait (3000000);
        //sio1_set_pos (KRS_ID2, pos2);
        //wait (300);
        //sio1_set_speed (KRS_ID2, speed);
```

```
            //wait (300);
            //sio1_set_stretch (KRS_ID2, stretch);
    //wait (300);
            com_echo_on ();
            //sio1_set_pos (KRS_ID3, pos3);
            //wait (300);
            //sio1_set_speed (KRS_ID3, speed);
            //wait (300);
            //sio1_set_stretch (KRS_ID3, stretch);
    //wait (300);
            //sio1_set_pos (KRS_ID4, pos4);
            //wait (300);
            //sio1_set_speed (KRS_ID4, speed);
            //wait (300);
            //sio1_set_stretch (KRS_ID4, stretch);
    //wait (300);
            //sio1_set_pos (KRS_ID5, pos5);
            //wait (300);
            //sio1_set_speed (KRS_ID5, speed);
            //wait (300);
            //sio1_set_stretch (KRS_ID5, stretch);
    //wait (300);
            //sio1_set_pos (KRS_ID6, pos6);
            //wait (300);
            //sio1_set_speed (KRS_ID6, speed);
            //wait (300);
            //sio1_set_stretch (KRS_ID6, stretch);
    //wait (300);
}
```

APPENDIX- F

Green Sweet Pepper Recognition System: Source Code

This is a part of sample code used in recognition of green sweet peppers algorithm. Some part of code and code for computation of fruit location and orientation is not included here due to copyright restrictions of OKA Laboratory.

```
////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
//                    File generated by HDevelop for HALCON/C++ Version 9.0                          //
////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
#include "HalconCpp.h"
#ifndef NO_EXPORT_MAIN
// Main procedure
void action()
{
  using namespace Halcon;
  // Local iconic variables
  Hobject  Image1, Red, Green, Blue, Hue, Saturation;
  Hobject  Value, Region, ConnectedRegions, SelectedRegions1;
  Hobject  ImageReduced1, Region1, ConnectedRegions1, RegionClosing1;
  Hobject  RegionOpening1, RegionTrans1, RegionDilation1, Circle1;
  Hobject  Image2, Region2, ConnectedRegions2, SelectedRegions2;
  Hobject  ImageReduced2, Region3, ConnectedRegions3, SelectedRegions3;
  Hobject  RegionClosing2, RegionOpening2, RegionTrans2, RegionDilation2;
  Hobject  Circle2, Image;
  // Local control variables
  HTuple  Pointer, Type, Width, Height, WindowHandle;
  HTuple  Area, Row, Column, Area1, Row1, Column1, Area2;
  HTuple  Row2, Column2, FGHandle1, FGHandle2;
  close_all_framegrabbers();
  open_framegrabber("PicPort", 1, 1, 0, 0, 0, 0, "default", 8, "rgb", -1, "false",
     "NTSC_RS170", "Picport Color:1", 1, 1, &FGHandle1);
  grab_image(&Image1, FGHandle1);
  get_image_pointer1(Image1, &Pointer, &Type, &Width, &Height);
  if (HDevWindowStack::IsOpen())
    close_window(HDevWindowStack::Pop());
  set_window_attr("background_color","black");
  open_window(0,0,Width,Height,0,"","",&WindowHandle);
  HDevWindowStack::Push(WindowHandle);
  if (HDevWindowStack::IsOpen())
    disp_obj(Image1, HDevWindowStack::GetActive());
  if (HDevWindowStack::IsOpen())
    set_colored(HDevWindowStack::GetActive(),12);
  if (HDevWindowStack::IsOpen())
    set_draw(HDevWindowStack::GetActive(),"margin");
  if (HDevWindowStack::IsOpen())
  set_line_width(HDevWindowStack::GetActive(),3);
 equ_histo_image(Image1, &Image1Histo)
 decompose3(Image1Histo, &Red, &Green, &Blue);
  trans_from_rgb(Red, Green, Blue, &Hue, &Saturation, &Value, "hsv");
  threshold(Value, &Region, 40, 180);
  connection(Region, &ConnectedRegions);
  select_shape_std(ConnectedRegions, &SelectedRegions1, "['area', 'anisometry']", "[2500,0],
[32500, 1.6]");
```

```
 area_center(SelectedRegions1, &Area, &Row, &Column);
 reduce_domain(Hue, SelectedRegions1, &ImageReduced1);
 threshold(ImageReduced1, &Region1, 40, 80);
 connection(Region1, &ConnectedRegions1);
 select_shape_std(ConnectedRegions1, &SelectedRegions1, "[‘area’, ‘anisometry’]", “[2500,0],
[32500, 1.6]”);
 closing_circle(SelectedRegions1, &RegionClosing1, 15.5);
 opening_circle(RegionClosing1, &RegionOpening1, 10.5);
 shape_trans(RegionOpening1, &RegionTrans1, "convex");
 dilation_circle(RegionTrans1, &RegionDilation1, 12.5);
 area_center(RegionDilation1, &Area1, &Row1, &Column1);
 gen_circle(&Circle1, Row1, Column1, 7.5);
 open_framegrabber("PicPort", 1, 1, 0, 0, 0, 0, "default", 8, "rgb", -1, "false",
    "NTSC_RS170", "Picport Color:1", 1, 1, &FGHandle2);
 grab_image(&Image2, FGHandle2);
 get_image_pointer1(Image2, &Pointer, &Type, &Width, &Height);
 if (HDevWindowStack::IsOpen())
   close_window(HDevWindowStack::Pop());
 set_window_attr("background_color","black");
 open_window(0,0,Width,Height,0,"","",&WindowHandle);
 HDevWindowStack::Push(WindowHandle);
 if (HDevWindowStack::IsOpen())
   disp_obj(Image2, HDevWindowStack::GetActive());
 if (HDevWindowStack::IsOpen())
   set_colored(HDevWindowStack::GetActive(),12);
 if (HDevWindowStack::IsOpen())
   set_draw(HDevWindowStack::GetActive(),"margin");
 if (HDevWindowStack::IsOpen())
   set_line_width(HDevWindowStack::GetActive(),3);
equ_histo_image(Image2, &Image2Histo)
decompose3(Image2Histo, &Red, &Green, &Blue);
 trans_from_rgb(Red, Green, Blue, &Hue, &Saturation, &Value, "hsv");
 threshold(Value, &Region2, 40, 180);
 connection(Region2, &ConnectedRegions2);
 select_shape_std(ConnectedRegions2, &SelectedRegions2, "[‘area’, ‘anisometry’]", “[2500,0],
[32500, 1.6]”);
 area_center(SelectedRegions2, &Area2, &Row2, &Column2);
 reduce_domain(Hue, SelectedRegions2, &ImageReduced2);
 threshold(ImageReduced2, &Region3, 40, 90);
 connection(Region3, &ConnectedRegions3);
 select_shape_std(ConnectedRegions3, &SelectedRegions3, "[‘area’, ‘anisometry’]", “[2500,0],
[32500, 1.6]”);
 closing_circle(SelectedRegions3, &RegionClosing2, 15.5);
 opening_circle(RegionClosing2, &RegionOpening2, 10.5);
 shape_trans(RegionOpening2, &RegionTrans2, "convex");
 dilation_circle(RegionTrans2, &RegionDilation2, 12.5);
 area_center(RegionDilation2, &Area2, &Row2, &Column2);
 gen_circle(&Circle2, Row2, Column2, 7.5);
 if (HDevWindowStack::IsOpen())
   disp_obj(Image1, HDevWindowStack::GetActive());
 if (HDevWindowStack::IsOpen())
   set_draw(HDevWindowStack::GetActive(),"margin");
 if (HDevWindowStack::IsOpen())
   set_color(HDevWindowStack::GetActive(),"red");
 if (HDevWindowStack::IsOpen())
```

```
    set_line_width(HDevWindowStack::GetActive(),2);
  if (HDevWindowStack::IsOpen())
    disp_obj(RegionOpening1, HDevWindowStack::GetActive());
  if (HDevWindowStack::IsOpen())
    set_line_width(HDevWindowStack::GetActive(),2);
  if (HDevWindowStack::IsOpen())
    disp_obj(RegionTrans1, HDevWindowStack::GetActive());
  if (HDevWindowStack::IsOpen())
    set_draw(HDevWindowStack::GetActive(),"fill");
  if (HDevWindowStack::IsOpen())
    set_color(HDevWindowStack::GetActive(),"red");
  if (HDevWindowStack::IsOpen())
    disp_obj(Circle1, HDevWindowStack::GetActive());
  set_window_attr("background_color","black");
  open_window(0,0,Width,Height,0,"","",&WindowHandle);
  HDevWindowStack::Push(WindowHandle);
  if (HDevWindowStack::IsOpen())
    disp_obj(Image2, HDevWindowStack::GetActive());
  if (HDevWindowStack::IsOpen())
    set_draw(HDevWindowStack::GetActive(),"margin");
  if (HDevWindowStack::IsOpen())
    set_color(HDevWindowStack::GetActive(),"red");
  if (HDevWindowStack::IsOpen())
    set_line_width(HDevWindowStack::GetActive(),2);
  if (HDevWindowStack::IsOpen())
    disp_obj(RegionOpening2, HDevWindowStack::GetActive());
  if (HDevWindowStack::IsOpen())
    set_line_width(HDevWindowStack::GetActive(),2);
  if (HDevWindowStack::IsOpen())
    disp_obj(RegionTrans2, HDevWindowStack::GetActive());
  if (HDevWindowStack::IsOpen())
    set_draw(HDevWindowStack::GetActive(),"fill");
  if (HDevWindowStack::IsOpen())
    set_color(HDevWindowStack::GetActive(),"red");
  if (HDevWindowStack::IsOpen())
    disp_obj(Circle2, HDevWindowStack::GetActive());
  // stop(); only in hdevelop
}
#ifndef NO_EXPORT_APP_MAIN
int main(int argc, char *argv[])
{
  using namespace Halcon;
  // Default settings used in HDevelop (can be omitted)
  set_system("do_low_error","false");
  action();
  return 0;
}
#endif
#endif
```

APPENDIX- G

Multispectral Sweet Pepper Recognition System: Source Code

This is a part of sample code used in multispectral recognition system to distinguish sweet peppers. Some part of code and code for maturity determination of detected fruits is not included here due to copyright restrictions of OKA Laboratory.

```
//////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
//                    File generated by HDevelop for HALCON/C++ Version 9.0                    //
//////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
#include "HalconCpp.h"
#ifndef NO_EXPORT_MAIN
// Main procedure
void action()
{
using namespace Halcon;
// Local iconic variables
Hobject  Image, R, G, B, H, S, V, Region, ConnectedRegions;
Hobject  SelectedRegions, ConnectedRegions1, RegionClosing;
Hobject  RegionOpening, RegionTrans, RegionDilation;
// Local control variables
HTuple  Pointer, Type, Width, Height, WindowHandle;
read_image(&Image, "Sweet_Pepper_1.tif");
get_image_pointer1(Image, &Pointer, &Type, &Width, &Height);
if (HDevWindowStack::IsOpen())
close_window(HDevWindowStack::Pop());
set_window_attr("background_color","black");
open_window(0,0,Width,Height,0,"","",&WindowHandle);
HDevWindowStack::Push(WindowHandle);
equ_histo_image(Image, &ImageHisto)
hom_mat2d_translate(ImageHisto2D, &0.5, &0.5, &ImageHisto2DTmp)
hom_mat2d_translate_local(ImageHisto2DTmp, &-0.5, &-0.5, ImageHisto2DAdapted)
projective_trans_region(ImageHisto, &TransRegion, &ImageHisto2DAdapted, 'bilinear')
projective_trans_pixel(ImageHisto2DAdapted, "[Row - 1,Row - 1,Row + 1,Row + 1], [Column -
2,Column + 1,Column + 1,Column - 1]", &RowTrans, &ColTrans, "", &ImageP)
proj_match_points_ransac(Image, &ImageP, &Rows1, &Columns1, &Rows2, &Columns2, 'ncc',
&34, &0, &0, &Height, &Width, &0, &0.5, 'normalized_dlt', &2, &42, &HomMat2DImage1,
&Points1Image1, &Points2Imag1)
projective_trans_image(ImageP, &Image1, &HomMat2DImage1, 'bilinear', 'false', 'false')
decompose3(Image1, &R, &G, &B);
trans_from_rgb(R, G, B, &H, &S, &V, "hsv");
threshold(V, &Region, 150, 180);
connection(Region, &ConnectedRegions);
select_shape(ConnectedRegions, &SelectedRegions, "['area', 'anisometry']", "[2222,0], [99999,
3.2]");
connection(SelectedRegions, &ConnectedRegions1);
closing_circle(ConnectedRegions1, &RegionClosing, 15.5);
opening_circle(RegionClosing, &RegionOpening, 15.5);
shape_trans(RegionOpening, &RegionTrans, "convex");
dilation_circle(RegionTrans, &RegionDilation, 12.5);
if (HDevWindowStack::IsOpen())
clear_window(HDevWindowStack::GetActive());
if (HDevWindowStack::IsOpen())
disp_obj(Image, HDevWindowStack::GetActive());
```

```
if (HDevWindowStack::IsOpen())
set_draw(HDevWindowStack::GetActive(),"margin");
if (HDevWindowStack::IsOpen())
set_color(HDevWindowStack::GetActive(),"red");
if (HDevWindowStack::IsOpen())
set_line_width(HDevWindowStack::GetActive(),2);
if (HDevWindowStack::IsOpen())
disp_obj(RegionOpening, HDevWindowStack::GetActive());
if (HDevWindowStack::IsOpen())
set_line_width(HDevWindowStack::GetActive(),3);
if (HDevWindowStack::IsOpen())
disp_obj(RegionTrans, HDevWindowStack::GetActive());
}
#ifndef NO_EXPORT_APP_MAIN
int main(int argc, char *argv[])
{
using namespace Halcon;
// Default settings used in HDevelop (can be omitted)
set_system("do_low_error","false");
action();
return 0;
}
#endif
#endif
```

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