2011

DEVELOPMENT OF A SEMI-AUTOMATED TOBACCO STRIPPING MACHINE UTILIZING STRING TRIMMERS

Robert George Sperry
University of Kentucky, rosperry06@gmail.com

ABSTRACT OF THESIS

DEVELOPMENT OF A SEMI-AUTOMATED TOBACCO STRIPPING MACHINE UTILIZING STRING TRIMMERS

Conventional stripping of burley tobacco is labor intensive and typically requires 50 to 75 worker hours per acre (wkr•hr/ac). The goal of the project was to reduce labor by optimizing leaf removal by string trimmer heads using combinations of strings lengths and motor speeds. In tests conducted on a single grade, all leaves outside the grade were removed by hand. Plants were run through the machine for sting lengths of 5, 7 and 9 inches and associated motor speeds which were monitored and recorded. Stripping efficiencies were calculated for each plant and collectively for each set of four plants. The machine was then tested for three grade stripping efficiency. Particle size analysis tests were run to determine potential losses due to leaf shredding. Efficiencies for single grade testing ranged from 93 to 96% for optimal string length and speed combinations. Stripping three grades by machine resulted in an average of 97% efficiency. Potential losses due to shredding accounted for 5.6% of the total weight mechanically removed. It is believed that this stripping concept, implemented on a full scale four grade basis, could result in savings of at least 18 wkr •hr/ac [45 wkr•hr/ha].

KEYWORDS: Tobacco, Engineering, Leaf Removal, Tobacco Stripping Machine, Tobacco Mechanization.

Robert G. Sperry
Author's Signature

1-27-2011
Date

DEVELOPMENT OF A SEMI-AUTOMATED TOBACCO STRIPPING MACHINE UTILIZING STRING TRIMMERS

By

Robert George Sperry

Dr. John H. Wilhoit
Director of Thesis

Dr. Dwayne Edwards
Director of Graduate Studies

01-27-2011
Date

RULES FOR THE USE OF THESIS

Unpublished theses submitted for the Master's degree and deposited in the University of Kentucky Library are as a rule open for inspection, but are to be used only with due regard to the rights of the authors. Bibliographical references may be noted, but quotations or summaries of parts may be published only with the permission of the author, and with the usual scholarly acknowledgments.

Extensive copying or publication of the thesis in whole or in part also requires the consent of the Dean of the Graduate School of the University of Kentucky.

A library that borrows this thesis for use by its patrons is expected to secure the signature of each user.

Name	Date

THESIS

Robert George Sperry

The Graduate School

University of Kentucky

2011

DEVELOPMENT OF A SEMI-AUTOMATED TOBACCO STRIPPING MACHINE UTILIZING STRING TRIMMERS

Thesis

A thesis submitted in partial fulfillment of the requirements for the degree of Masters of Science in Biosystems and Agricultural Engineering at the University of Kentucky

By

Robert George Sperry

Lexington, KY

Director: Dr. John H. Wilhoit, Associate Professor, Biosystems and Agricultural Engineering

Lexington, KY

2010

ACKNOWLEDGEMENTS

I want to thank Dr. Scott Shearer for taking a chance on admitting a Physicist and giving me the opportunity to do what I love. He is a close friend who has helped guide me through the process of graduate school and life. I will forever be grateful to him for the experiences I had in the Biosystems and Agricultural Engineering Department.

I want to thank Dr. Wilhoit for being such a great friend, mentor and advisor. He was there to help and give encouragement throughout my entire graduate career. He was always there when I needed to talk about this project or about life. I want to thank both him and his wife Sue for being so hospitable and for making me feel at home.

I want to give special thanks to Dave Ash. He showed me the proper way to draft and taught me how to draw in AutoCAD. His invaluable advice and knowledge will help me though the rest of my career. I am pleased to call him my friend.

I want to thank all the guys at the shop. Carl King gave me guidance on several projects and was patient with me as I learned my way around. Lee Rechtin helped fabricate several parts for this project and was always there to bounce ideas off. Ed Hutchins gave me direction on wiring and welding, and was there to help me assemble, reassemble and move the machine. Brett Childers was always there to give me a hand on several projects and help me find tools and setup machines. Ed Roberts was around to talk to and give me advice and encouragement. All of these guys spent numerous hours helping me on this and many other projects during my time at the University of Kentucky. Without their expertise in machining none of this could have been completed.

I want to thank Mike Sama for helping me choose sensors and develop a program to input and log speeds. He has been an excellent teacher and advisor. I am thankful to have had the opportunity to work with such a talented individual.

I want to thank Dr. George Duncan, Dr. Larry Wells, Dr. Bob Pearce and Dr. Tim Stombaugh for sitting on my committee and helping point me in the right direction to get this project completed. Without their vast knowledge and experience, this project would not have gone as smooth as it did. I especially want to thank Dr. Stombaugh for helping me learn about and work with circuits and components. I consider this knowledge invaluable.

I want to thank my wife Kelly for her support and for being there to push me along when progress on my thesis slowed. I want to thank her for helping me edit for grammar and punctuation when I felt like I could not look at my thesis any longer.

I would like to thank my in-laws, Phil and Patty Carter, for all their support and encouragement. I want to thank them for being patient when my papers and books were scattered all over the kitchen table. They were always there to listen to my frustrations.

Most of all I want to thank my parents who pushed me to achieve what seemed to be beyond my reach. They guided me and supported me throughout my entire college career. I want to thank them for being such great parents and for all their love. I hope that someday I can repay them for all they have done.

I want to thank everyone who has helped me through this long journey toward achieving my masters degree. I am privileged to have been surrounded by such great people and friends.

TABLE OF CONTENTS

Acknowledgements iii

Definitions vii

List of Tables viii

List of Figures ix

Chapter One – Introduction 1

- 1.1 Preface 1
- 1.2 Purpose of Research 2
- 1.3 Objectives 3

Chapter Two – Literature Review 4

- 2.1 Conventional Stripping of Burley Tobacco 4
- 2.2 Stripping Conveyors 5
  - 2.2.1 Range Carousel System 5
  - 2.2.2 Stripping Wheel 6
  - 2.2.3 Single-Chain Stalk Conveyor 7
  - 2.2.4 Dual Chain Stick Conveyor 8
  - 2.2.5 Gathering Belt Conveyor 9
- 2.3 Leaf Removal Aids 11
  - 2.3.1 Counter-Revolving Wiper Stripper 11
  - 2.3.2 Clamp Stripper with Leaf Separator 12
  - 2.3.3 Knot-Hole Strippers 13
  - 2.3.4 Three Grade Roller Stripping Machine 14
  - 2.3.5 Roller Stripper 15
- 2.4 Semi-Automated Stripping Machines 17
  - 2.4.1 Semi-Automated Stripping and Sorting Machine 17
  - 2.4.2 French Roller Stripping Machine 19
  - 2.4.3 Beater Bar Stripper Grader Machine 19
- 2.5 Summary 21

Chapter Three –Machine Design, Development, and Fabrication 23

- 3.1 Proposed Solution 23
- 3.2 Preliminary Configuration 24
  - 3.2.1 Stalk Conveyance 24
  - 3.2.2 Stalk Holding 25
  - 3.2.3 Leaf Orientation 27
  - 3.2.4 Leaf Removal 29

3.2.5 Grading and Coverage 32
3.3 Final Experimental Configuration 33

Chapter Four – Experimental methods 37

4.1 Geometric Analysis for Coverage...37
4.2 Speed Measurements and Recording 39
4.2.1 Bench Testing 39
4.3 Procedure for Single Grade Stripping Efficiency Tests...42
4.4 Procedure for Three Grade Stripping Efficiency Tests..45
4.5 Procedure for Particle Size Analysis...48

Chapter Five – Results and Evaluation 52

5.1 Statistical Analysis..52
5.2 Single Grade Stripping...53
5.3 Three Grade Stripping..56
5.4 Particle Size Analysis 57
5.5 Graphical Motor Speed Analysis..58
5.5.1 Visual Analysis 58
5.5.2 Energy Approximation Analysis...61
5.6 Productivity and Economic Considerations...65

Chapter Six – Conclusions and Recommendations 68

6.1 Cups 68
6.2 Brushes...68
6.3 Grading 69
6.4 Conveyor Speed...70
6.5 Power Requirements and Usage 70
6.6 Conclusion 71

Appendices...72

Appendix A 72
Appendix B 74
Appendix C 76
Appendix D 78
Appendix E 80

References..81

Vita...83

LIST OF TABLES

Table 1: Hand stripping ranges for different string lengths...43

Table 2: String length and motor speed test combinations...43

Table 3: ANOVA for speed and length interactions...52

Table 4: Stripping efficiencies with standard deviations for 5 in. string length................54

Table 5: Stripping efficiencies with standard deviations for 7 in. string length................54

Table 6: Stripping efficiencies with standard deviations for 9 in. string length................54

Table 7: Optimal speeds for each string length 55

Table 8: Results for full plant stripping efficiency 56

Table 9: Sizes of tobacco leaf pieces after being stripped by machine 58

Table 10: ANOVA to determine goodness of fit of the model...74

Table 11: Tukey mean calculation for string length and speed combinations..................74

Table 12: Tukey comparison of mean of string length and speed combinations..............75

Table 13: Results of dynamic analysis..76

Table 14: Estimated cost of a production-model stripping machine. 81

LIST OF FIGURES

Figure 2.1: Simplified diagram of the Range Carousel 6

Figure 2.2: Stripping Wheel...7

Figure 2.3: Workers stripping tobacco using a dual chain stick conveyor 9

Figure 2.4: Straight line conveyor using corrugated belting..10

Figure 2.5: Counter revolving wiper stripper 12

Figure 2.6: Clamp stripper with leaf separator 13

Figure 2.7: Golden Leaf knot-hole stripper 14

Figure 2.8: Three grade Patterson stripping machine 15

Figure 2.9: Roller stripper for stalk cut tobacco 17

Figure 2.10: Semi-automated stripping and sorting machine 18

Figure 2.11: Beater bar stripper grader machine made by Carolina Tobacco Services (CTS) 21

Figure 3.1: Basic configuration of stripping machine concept..24

Figure 3.2: Illustration of fixed cup size with a range of stalk sizes 26

Figure 3.3: Leaves oriented opposite the direction of travel to optimize detachment by string trimmers..27

Figure 3.4: Brush setup which allowed for changes in brush angle 28

Figure 3.5: Stalk parallel to the cutting plane of the trimmer head and moving in the direction of the arrow 30

Figure 3.6: Configuration of the machine used for testing 34

Figure 3.7: Spring-loaded cup for holding the tobacco plants..35

Figure 4.1: Four grade coverage for 48 in. plants 38

Figure 4.2: Stalk coverage area for different string lengths... 39

Figure 4.3: Circuit diagram for Hall effect sensor 40

Figure 4.4: Scale and platform used to weigh the tobacco plants...................................... 44

Figure 4.5: Three string coverage using 7 in. strings.. 46

Figure 4.6: Three grades stripped by machine.. 47

Figure 4.7: Plate scale converted into a hanging scale 49

Figure 4.8: Sorting results from a particle size analysis test.. 51

Figure 5.1: Motor speed versus time for an initial motor speed of 2200 rpm with string length of 9 in. 59

Figure 5.2: Motor speed versus time for an initial motor speed of 2800 rpm with string length of 9 in. 61

Figure 5.3: Acceleration difference (Tp/I) for all of the motor speed and string length combinations... 64

DEFINITIONS

- Case – The condition of the tobacco stalk and leaves when ready for stripping based on the moisture content of the leaves.
- Flyings – Bottom grade of the tobacco plant near the cut end of the stalk
- Grading – Sorting the leaves into the proper groups based on stalk position, color and maturity.
- Leaf- Third grade up from the bottom of the plant
- Lug- Second grade up from the bottom of the plant
- Non-relay Stripping - One worker strips all grades of the plant
- Relay Stripping - A chain of workers where each worker only strips one grade before passing the plant on to the next worker
- Shredding – The tearing of the tobacco leaf into pieces
- String Trimmer-A device that utilizes a string for cutting grass and weeds (e.g. Weed Eater ®)
- Stripping – Removing tobacco leaves from the stalk either by hand or machine.
- Stripping Efficiency – Based on weight, the percentage of tobacco leaves and stems removed from the stalk by the string trimmers compared to a 100% leaf and stem removal.
- Stick – A wooden stick containing an average of 6 plants of tobacco.
- Tip- Top grade

CHAPTER ONE – INTRODUCTION

1.1 Preface

Burley tobacco is an extremely labor intensive crop when compared to most crops grown. The production of an acre of tobacco requires between 160 to 200 worker hours (Duncan, 2006c). The inability to mechanize such a complex plant type is the main reason for the large labor requirements in tobacco production. Most of the burley tobacco grown in the United States is still harvested by hand using relatively primitive machinery and tools. Spraying, tillage and transplanting equipment have automated certain aspects of production, but most of the manual labor involved in producing tobacco has not yet been eliminated. Recent introductions of harvesting machinery have the potential to help reduce labor requirements on larger farms that are able to afford the capital-intensive developments, but the smaller farms are relegated to continue with time consuming techniques. Furthermore, very little has been done to assist in the most labor intensive phases of production such as harvesting, hanging and stripping.

Tobacco production can be split into four main phases: transplant production, tilling/planting/field growth, harvesting/hanging/curing, and stripping/baling. Of the total labor required to produce an acre of tobacco, stripping is the most labor intensive part of the whole process, typically requiring 50 to 75 worker hours per acre [125 to 188 wkr•hr/ha] (Duncan, 2006c). Typical hand stripping is tedious and slow. It involves the workers removing and separating each grade of leaves by hand from approximately 7000 stalks per acre [17500 stalks/ha]. After the leaves are removed, they are placed in collection boxes based on grade. The leaves from the boxes are then pressed into large tobacco bales to be sold.

Tobacco is a high-valued crop typically yielding over $4000 per acre in gross returns (Foreman, 2006). There are many farms that derive a significant portion of their income from relatively small acreages of tobacco. These farms simply do not have the quantity of flat land needed to gross the same in corn or soybeans. The trend in tobacco farm size is increasing due to tobacco companies cancelling contracts with smaller farmers, as the consumption of tobacco-related products in the United States and worldwide declines. Fuel prices are up, domestic labor for tobacco production is scarce, and legal immigrant labor is expensive. Mechanization in tobacco production is necessary to help reduce labor requirements, cut costs, and keep tobacco farming an economically viable enterprise.

1.2 Purpose of Research

Domestic burley tobacco production is suffering. With few mechanical aids for producing the crop, the required labor and associated costs to produce burley tobacco are high. These difficulties are causing many smaller tobacco farms to go out of business and larger tobacco farms to produce more. On some larger farms quality is declining due to lack of manpower to tend to the delicate crop.

The main purpose of this research was to develop and test a cost effective semi-automated stripping apparatus that can significantly reduce labor requirements. The key element of this semi-automated mechanical stripping concept is the removal of tobacco leaves from an upright plant held at the cut end using a flexible trimmer string that is strong enough to detach the stems, yet gentle enough to leave the stalk intact. Furthermore, by adjusting string length for specific sections of stalk, the entire plant could be stripped and accurately graded based on its linear travel along a conveyor (see Figure 3.1). The focus of this project was the optimization of leaf removal for different string lengths by varying motor speeds for a preset conveyor velocity of 0.73 ft/s [23 cm/s]. Combining both the stripping and mechanical grading, this concept could result in a low-cost automated system for stripping burley tobacco.

1.3 Objectives

The goal of this study was to design, develop and test components of a mechanical system to reduce the manual labor requirements for stripping and grading burley tobacco while keeping leaf losses due to shredding to a minimum. The specific objectives were to:

1. Develop a mechanical system for removing a single grade of burley tobacco from the stalk utilizing string trimmer technology.
2. Determine the best combination of motor speeds and string lengths for optimal stripping efficiency.
3. Strip tobacco leaves into three appropriate grades based on stalk position and linear progression along the length of the machine using multiple string trimmers.
4. Evaluate the stripped leaves for damage due to shredding based on a particle size distribution to help classify potential losses.

CHAPTER TWO - LITERATURE REVIEW

2.1 Conventional Stripping of Burley Tobacco

Conventional stripping of burley tobacco consists of workers removing leaves from the cured burley plant by applying pressure by hand to the stem of the leaf where it attaches to the stalk. One worker is usually assigned to remove one grade of leaf and then pass the plant to the next worker who removes the next grade. This sequence continues until all grades are removed. The last worker deposits the leafless stalk in a group for subsequent disposal. The stalks are usually disposed of by spreading them back onto the field. Sometimes the bare stalks are sent through a stalk chopper to make them easier to handle and to decrease decomposition time. Stripping is traditionally done in a small room attached to the tobacco housing facility. It is done between the months of November and February at times when the moisture content of the air is sufficient to maintain a pliable leaf so that shattering of the leaf does not reduce yield. Duncan (2006c) estimated the labor requirements to strip a crop of burley tobacco to range from 50 to 75 worker hours per acre (wkr•hr/ac) [125 to 190 wkr•hr/ha], which is nearly one third the total labor required to produce the tobacco crop.

2.2 Stripping Conveyors

2.2.1 Range Carousel System

In the early 1980's, Alfred Range of Johnson City, TN developed a system to aid in the mechanics of removing tobacco leaves from the plant (Range, 1984). This system, commonly referred to as the Range Carousel system, aimed to reduce labor by decreasing the worker movement. Furthermore, it improved stripping efficiency by freeing up both hands to use for stripping. Range's carousel consisted of a base with a rotating top containing arms that stuck out in a spoke-like manner to hold sticks of tobacco. A generalized drawing of the machine can be seen in Figure 2.1. Workers would stand around the carousel, each pulling off one grade. After a worker pulled off their assigned grade, the carousel was rotated to the next worker who pulled off their grade. The carousel was rotated until the empty stalks were at a position where the stripped stalks and stick were removed and a new stick could be loaded without interfering with the stripping of the other stalks.

Range's carousel system was a huge development at that time over the conventional non-relay systems. It allowed for handling plants on sticks which permitted stripping in dryer conditions with less of a risk of leaf shattering. Furthermore, it allowed for both hands to be used during stripping, and it reduced the amount of walking required by each worker. Isaacs and Mundy (1988) reported that the carousel system tested led to reductions in labor from 27% to 49% over the conventional method, a very large reduction for a machine still utilizing hand stripping.

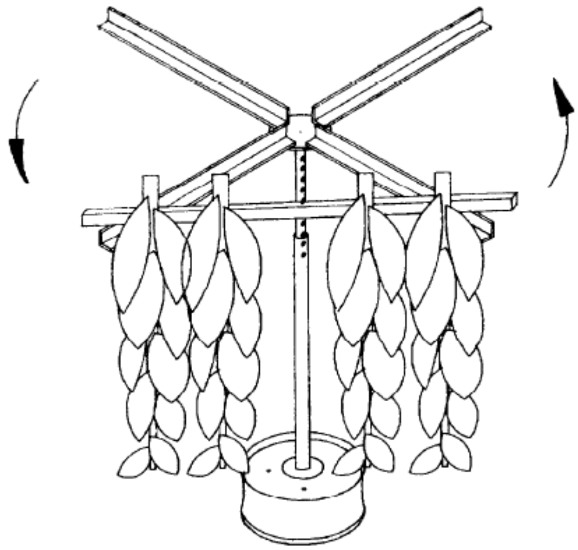


Figure 2.1: Simplified diagram of the Range Carousel.

2.2.2 Stripping Wheel

The stripping wheel (see Figure 2.7) is a circular frame-style conveyor that holds the plants loosely at the cut end in 2 in. x 2 in. [5 cm x 5 cm] flared cups and slowly conveys them past the workers (Figure 2.2). This rotating frame setup, powered by a small variable speed motor drive, was designed and constructed to utilize the increase in productivity found from having a relay style stripping operation, where each worker removes only one grade of the plant. The main advantage of the stripping wheel is that it frees up the worker's hand that would normally be holding the stalk while their other hand strips the plant. Furthermore, for the stripping wheel in particular, the plants are oriented cut end down which has been found to increase ease and speed of stripping when compared with other relay stripping conveyors, such as the Range Carousel system (Isaacs and Mundy, 1988), where the cut end is up. Studies conducted at the University of Kentucky showed that labor requirements decreased from 73 to 51 wkr•hr/ac [183 to 128 wkr•hr/ha] through the implementation of the stripping wheel (Duncan, 2006c), a 30% saving in labor over conventional hand stripping operations.

Figure 2.2: Stripping wheel.

2.2.3 Single-Chain Stalk Conveyor

The single-chain stalk conveyor is a straight line version of the stripping wheel. Cups spaced about every two feet are attached to a chain that runs in a track at waist level. Plants are placed in the cups at one end of the conveyor and are moved past several workers. Each worker removes one grade and places it in a bale box (Shirley and Duncan, 2005). This stripping concept was a relay-based operation that eliminated hand-passing of the plants to the next worker, which improved the ergonomics and productivity of the system. When the plant reached the end of the conveyor, all grades had been stripped, and the stalk was removed from the cup and the cup travelled under the conveyor and back to the loading position. While not a fully automated machine, the basic concept of holding plants at one end and conveying them past workers or through stationary stripping devices has become an important element in the design of some tobacco stripping machines.

2.2.4 Dual Chain Stick Conveyor

The dual chain stick conveyor is essentially a 10-18-ft [3.0-5.5-m] long straight-line version of the of the Range Carousel system. Tobacco is spread to either edge of the sticks (to accommodate the conveyor) and then placed on the conveyor and moved past a crew of workers on both sides of the plant (Figure 2.3). As the plant progresses up the inclined conveyor it is stripped from cut end to tip with each worker removing one grade (Duncan, 2006b). The main benefits of this system are the ability to handle somewhat drier tobacco, the increased efficiency due to relay style stripping and the increased speed of stripping due to two-handed stripping. Stripping rates of 40 or more stalks per minute for 7-10 workers were observed (Duncan, 2007). This is an equivalent labor requirement ranging from 22 to 31 wkr•hr/ac [51 to 58 wkr•hr/ha] for stripping alone. If two workers are used for baling, the total labor requirement becomes 28 to 38 wkr•hr/ac [70 to 94 wkr•hr/ha].

Figure 2.3: Workers stripping tobacco using a dual chain stick conveyor.

2.2.5 Gathering Belt Conveyor

One straight line conveyor system used to increase the productivity of stripping burley tobacco employed gathering belts to convey stalks past workers (Figure 2.4). Two opposed corrugated belts running parallel to each other grabbed and held the base of the tobacco stalk as it traveled the 17-ft [5.2 m] length of the conveyor. Workers removed individual grades of tobacco as the plant passed them (Duncan, 2006a). Increased productivity due to two-hand relay stripping by workers located on either side of the conveyor made this a fast alternative to conventional stripping. Furthermore, the lack of metal gears or exposed steel chain made this a safer alternative to some stripping techniques.

Being safer does have its drawbacks. As seen in the video footage, the belting does not hold the stalks rigidly and consistently. This could hinder worker performance by making the stripping of each plant a unique motion instead of a repeatable one.   Labor rates for stripping alone for this conveyor were observed at approximately 50 stalks per minute for 9 workers stripping (Duncan 2006a). This was approximately 21 wkr•hr/ac [53 wkr•hr/ha] for stripping. If two workers are used for baling, the total labor requirement becomes 28 wkr•hr/ac [69 wkr•hr/ha].

Figure 2.4: Straight line conveyor using corrugated belting.

2.3 Leaf Removal Aids

2.3.1 Counter-Revolving Wiper Stripper

The counter-revolving wiper stripper (Figure 2.5) was a single grade stripping machine. Cured tobacco plants were placed tip-end first onto a conveyor where they entered the guide rollers of the machine. The conveyor pushed the tips into the counter revolving wiper blades that severed the leaves from the stalk. The wiper blades had a half moon notch to encompass the entire circumference of the stalk, and they were mounted on a spring loaded cantilever arm to accommodate different diameter of stalks (Morrison and Yoder, 1973). Once the tip end got to the fluted rollers, it progressed through the rest of the defoliation process and ejected the bare stalk onto the ground. Morrison and Yoder (1972) measured labor requirements with this machine ranging from 28.4 wkr•hr/ac [71 wkr•hr/ha], when malfunctions were occasional, to 50.8 wkr•hr/ac [127 wkr•hr/ha] when stalk breakage and plugging of the machine was high. This machine (along with the knot-hole stripper, to be described in a later section) was functionally a very effective stripping machine, but the inability to mechanically separate different leaf grades was a serious limitation.

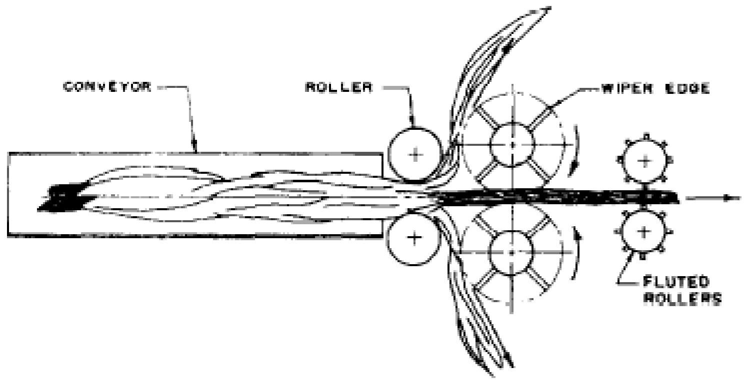


Figure 2.5: Counter revolving wiper stripper.

2.3.2 Clamp Stripper with Leaf Separator

Pinkham (1981) patented a machine design intended to mimic hand stripping. It mechanically clamped the leaves and then forced the leaves opposite their direction of growth by conveying the stalk forward. According to the patent, in order to operate the machine, a plant was placed on the horizontal feed bars at the left of the machine (Figure 2.6). As the metal cups attached to the chain moved around the sprocket it picked up the plant and moved it past the leaf orientation and separation bars. This ensured that the leaves were spread out so that when the plant was laid on the conveyor there was an equal distribution of leaves on either side. The plant was then conveyed horizontally for a short distance when a cam released two clamps that grasped the leaves on either side of the conveyor. The plant was then conveyed out the right side of the machine as the leaves were pulled from the stalk. The leaves removed by the machine then fell onto a conveyor maintaining their same stalk position and thus proper grade. Another worker then removed each grade and deposited it in the proper box for baling. This machine could be operated in a continuous manner and is one of the first patented designs for a fully automated three grade stalk stripping machine.

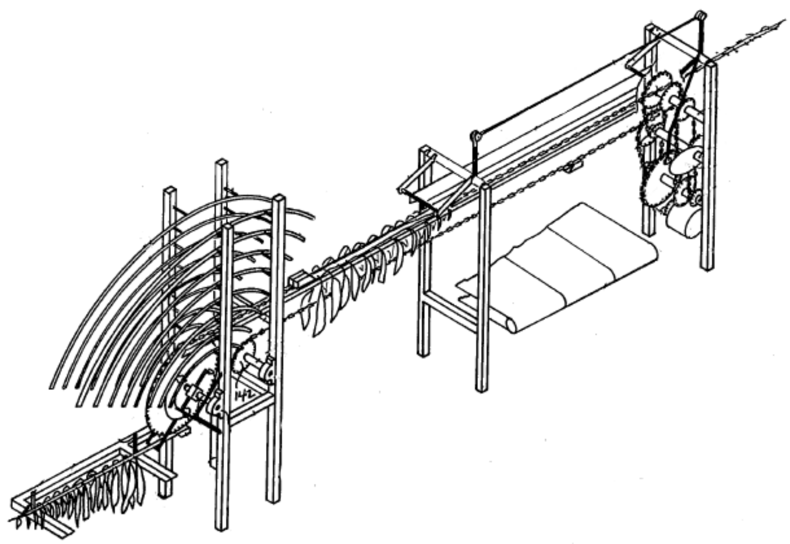


Figure 2.6: Clamp stripper with leaf separator.

2.3.3 Knot-Hole Strippers

In the early 1980's there was a mass influx of what were referred to as Knot-Hole strippers. Duncan and Tapp (1984) tested several different variations of this machine being produced by different manufacturers. The basic operation of these machines, one of which is seen in Figure 2.7, involved a worker feeding a plant through the machine tip end first. The tip of the plant would enter a set of four overlapping spring-pressured metal plates. A small half-circle opening on each plate would remove the leaves as the plant was propelled through the plates opening. In the machine, a set of rollers would grasp the stalk and start conveying it through the plates. As the plant progressed, the plate opening would expand to accommodate the increase in stalk diameter. Assuming an average yield of 2500 lb/ac [2800 kg/ha], these machines did a good job of stripping leaves from the stalk with a range in labor requirements from 49 to 78 wkr•hr/ac [122 to 195 wkr•hr/ha], compared with 69 wkr•hr/ac [170 wkr•hr/ha] for hand stripping. Duncan and Tapp (1984) found that these machines on average left from 0.72% to 5.32% of useable tobacco on the stalk. The problem with this type of machine was that it was difficult to effectively grade tobacco. Tobacco was usually stripped into a single mixed grade that brought a lower price than the traditional three and four grades.

Figure 2.7: Golden Leaf knot-hole stripper.

2.3.4 Three Grade Roller Stripping Machine

The Patterson (1983) machine contained a series of three work stations, each for a different grade of tobacco. Each station contained a pair of rolling contact counter-rotating wheels spinning at 600 rpm (Figure 2.8). The plant grade to be stripped was placed over one set of wheels and rested on a stalk support. The rotating wheels grabbed the leaves and pulled them off, dropping them in a grade box below. The plant was then moved from station to station until all grades were removed. It was recommended by Paterson (1983) that three workers operate three separate stations to obtain maximum efficiency. During tests conducted by Duncan and Tapp (1984) to determine maximum efficiency (minimum labor required), labor requirements of 44 wkr•hr/ac [110 wkr•hr/ha] were observed. The machine is comparable to the roller stripper designed by Miyake and Manzawa (1989b), but it is simpler and presumably cheaper.

Figure 2.8: Three grade Patterson stripping machine.

2.3.5 Roller Stripper

The machine developed by Miyake and Manzawa (1989a) consisted of a pair of leaf-stripping rollers that were approximately the same length as the tobacco stalk to be stripped. The stripper rollers were in the horizontal plane and were in rolling contact with each other. The holding frame was above the rollers and was spaced in such a way that the gap between them was smaller than the tobacco stalk. Its purpose was to ensure that only the leaves came into contact with the stripping rollers. The operator stood on the side of the foot pedal (Figure 2.9) and laid a plant on the holding frame above the stripping rollers. The operator pressed the foot pedal which started the rollers rotating downward at the contact surfaces. There were a large number of looped ribbons on Miyake and Manzawa's (1989b) stripping rollers that created a draft and helped draw the leaves toward the rollers. The leaves were then pinched between the rollers and pulled from the stalk. Once they passed through the rollers a set of dividers kept the leaves separated in the correct grades based on their original stalk position.

Miyake and Manzawa (1989a) stated that, on average, their leaf stripping machine striped at twice the rate of manual stripping. On the five farms where the machine was tested, an average work rate of 331 plants/hr was observed. The machine required two workers: one operating the machine, and one baling the leaves. This work rate was equivalent to 43.4 wkr•hr/ac [109 wkr•hr/ha] assuming an average population of 7000 plants per acre [17500 plants/ha].

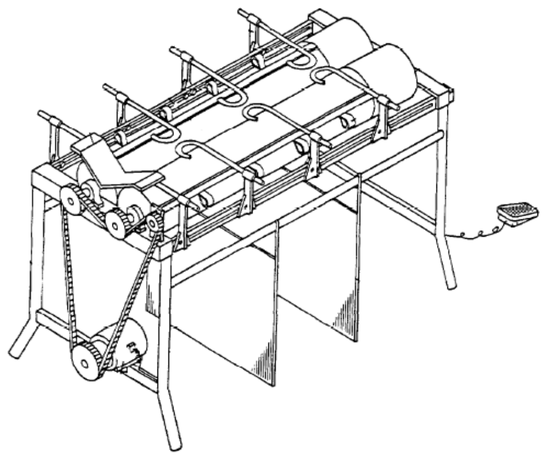


Figure 2.9: Roller stripper for stalk cut tobacco.

2.4 Semi-Automated Stripping Machines

2.4.1 Semi-Automated Stripping and Sorting Machine

Wells and Bader (1990) developed a semi-automated mechanical system for stripping and grading cured burley leaves. Horizontal stalks with the leaves hanging vertically were inserted cut end first into the machine. Two feed rollers grasped the base of the stalk and conveyed it into the machine where two opposed horizontal gathering belts grasped the leaves and removed them from the stalk. The leaves were dropped stem-end first onto a rotating carousel platform (Figure 2.10). A photo sensor linked to a cam through electric switches counted the leaves passing it and then rotated the carousel to allow the correct number of leaves to be placed in grading bins. Depending on setup, the number of leaves deposited in each grade could be controlled for different plant varieties and growing conditions.

This stripper/grader was designed for two workers. One worker placed stalks into the rollers while the other transferred sorted leaves from the carousel bins to baling boxes nearby. In the machine's optimal configuration, Wells and Bader (1990) determined that 97.6% of usable leaf material was removed from the plants tested and that the productivity of the machine was approximately 2.4 times that of traditional hand stripping. However, experiments also revealed that the photo sensor was not reliable when counting leaves removed, especially on the lower stalk positions. An average of 1.67 and 1.36 leaves in the flying and lugs, respectively, were improperly sorted which resulted in improper grading. They stated that further work needed to be done to improve both the sorting and grading of the leaves and the convenient disposal of stripped stalks.

Figure 2.10: Semi-automated stripping and sorting machine.

2.4.2 French Roller Stripping Machine

A new machine for stripping cured burley tobacco from the stalk has recently been developed in France. This semi-automated machine utilizes the proven method of pulling leaves from the stalk with opposed rollers. A cured plant is placed onto the machine horizontally, with the leaves hanging down vertically, where guide bars help separate the leaves into grades based on stalk position. The plant is moved forward laterally and into the stripping chamber to accommodate the loading of another plant. Once in position, two rotating rollers come together on the hanging tobacco leaves and pull them from the stalk (Eodiss Systems, 2010). Already having been separated by the grading guide bars upon loading, each group of leaves drops onto a conveyor and is conveyed to a baler. The machine was specifically made to be portable to allow farmers to cooperatively own and use it. No productivity numbers have been released but it appears to strip at least as effectively as all other semi-automated stripping machines.

2.4.3 Beater Bar Stripper Grader

A machine developed by Carolina Tobacco Services (CTS) has been in use for several years. The machine is about 16 ft [4.9 m] long, 4 ft [1.21 m] wide and approximately 8 ft [2.4 m] tall (Figure 2.11). Plants are fed tips first into a set of opposed sticker chains at the top of the machine after the tip grade has been removed by hand (Duncan and Wilhoit, 2007). The need to first strip the tips makes feeding the machine more labor intensive; about four workers are needed to maintain productivity. As the plant progresses through the machine, two sets of 12 ft [3.7 m] long beater bars with rubberized fingers rotate down to knock the cured tobacco leaves from the stalk. The stripped leaves fall below into one of four bale boxes underneath. Grading is accomplished by stalk position based on linear travel of the plant through the machine. After the plant has moved the entire length of the machine, the opposed sticker chains releases it, and it drops to the ground or onto a conveyor.

Excluding labor for baling, unpublished observations place the labor requirements of this machine at approximately 28.2 wkr•hr/ac [70.5 wkr•hr/ha] assuming average yields of 7000 plants per acre (Wilhoit, 2008). These are the highest recorded labor efficiency numbers seen from any semi-automated stripping machine to date. While this data indicates that this machine has high labor efficiency, it does have some drawbacks. The beater bars that remove the leaf from the stalk cost $2000 per set and only last for approximately 40 acres [16 ha]. This, combined with the high initial cost, approximately $32,000, lessens the appeal of the machine to farmers and decreases the overall profitability of the machine (CTGR, 2009). However, even with its drawbacks, this machine performs better than all other semi-automated stripping machines currently on the market and can significantly reduce the labor required to strip an acre of tobacco when compared with the alternative of hand stripping. Note that the high stripping performance numbers for some of the stripping aids were based on stalk counts from videos over short time intervals.

Figure 2.11: Beater bar stripper grader machine made by Carolina Tobacco Services (CTS).

2.5 Summary

Many tobacco stripping techniques and machines have been developed in the past, but none have been widely adopted by producers. High initial cost, inability to grade, and poor performance have contributed to the lack of interest. Automated stripping by machine is a complicated issue that to this point has not been successfully accomplished to the growers' satisfaction.

A system has been proposed that combines proven technology for conveying plants and cutting fibrous organic material. This system should be far less expensive than other semi-automated machines and substantially reduce labor and costs for producing stalk-cured tobacco. The proposed machine will be able to strip into four grades - three mechanically and one by hand. It could be especially beneficial for small to mid-size tobacco growers.

CHAPTER THREE – MACHINE DESIGN, DEVELOPMENT, AND FABRICATION

3.1 Proposed Solution

A mechanical burley tobacco stripping machine was proposed to reduce the manual labor requirements for stripping and grading burley tobacco while keeping leaf losses due to shredding to a minimum. Miyake and Manzawa (1989a) stated that grading by stalk position was preferred to grading by visual inspection of individual leaves themselves. In accordance with this research, the proposed machine needed to strip and grade based on stalk position. The design utilized the effectiveness of cutting with a string trimmer along with the gentleness achieved by using a flexible plastic string rather than metal blades. With the proposed design, a worker would remove the flyings grade by hand and place the plant in the machine. The stalk would then be conveyed past three stationary string trimmer heads. The trimmers would remove the lug, then the leaf and finally the tip grades and allow each to fall into a separate grade box for easy removal and baling (Figure 3.1). The ultimate goals for this design were to reduce labor, ease work and save money with a semi-automated stripping/grading machine.

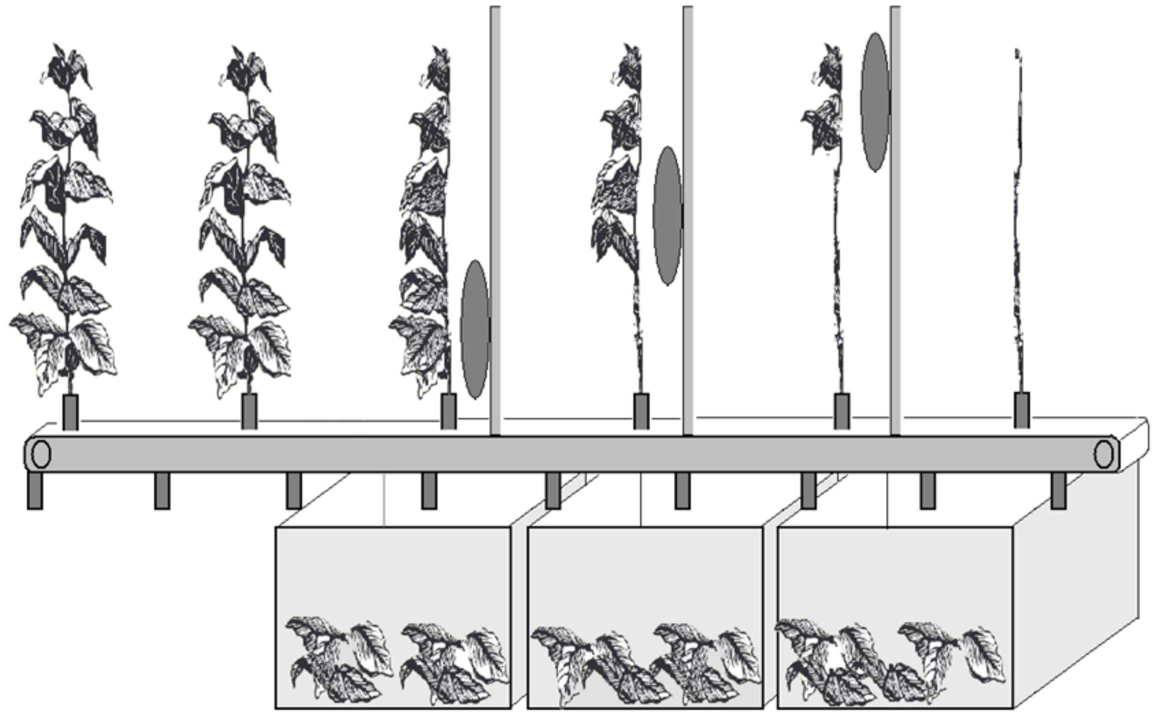


Figure 3.1: Basic configuration of stripping machine concept.

3.2 Preliminary Configuration

3.2.1 Stalk Conveyance

Based on past tobacco research and machine design, there are two main choices in tobacco conveyor designs: straight line conveyors and circular conveyors. The stripping wheel and Range carousel are types of circular tobacco conveyors that meet space and cost requirements by being very simple and compact. The sticker chain system of the beater bar stripper grader and the gathering belt system are both examples of straight line conveyors. These conveyors are usually more complex, expensive and require more space. They are generally custom made for the individuals to meet their requirements. Due to availability, space requirements and simplicity, the initial trial of the concept was carried out on a readily available circular stripping wheel conveyor.

Preliminary testing was preformed with the stripping wheel and inexpensive off-the-shelf string trimmers. Based on several days of testing and experience with the setup, it became apparent that the plane of the string needed to be parallel to the stalk and perpendicular to the direction of travel to obtain the best results. Aligning the trimmers in this fashion to conduct a series of tests with the stripping wheel setup was difficult and time consuming. It became evident that the best chance for producing a successful machine was to use a straight line conveyor.

3.2.2 Stalk Holding

In the interest of simplicity, the first design was a cup made of 2 in. x 2 in. [5 cm x 5 cm] square steel tubing 6 inches high that loosely held the tobacco plant as it traveled through the conveyor. Similar cup holders are used on stripping wheels. However, due to the variability in plant stalk diameters occurring from growing conditions, the cups were unable to hold stalks in a consistent and vertical position for moving past the string trimmer (see Figure 3.2). Smaller diameter plants tended to lean backwards more than large diameter stalks. The inconsistency in the stalk's orientation created trimmer alignment issues that severely decreased stripping efficiency and increased string wear. The cups' sharp edges also frequently cut the string when trying to strip the lower grades.

Furthermore, the cups allowed the stalks to bounce and lean away from the string trimmers because they were not held rigidly.

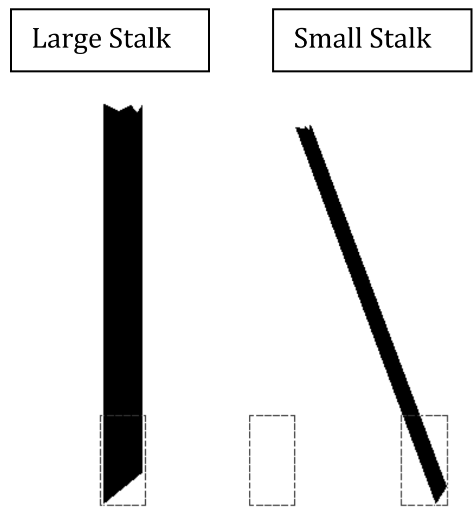


Figure 3.2: Illustration of fixed cup size with a range of stalk sizes.

Several gripping options were considered. Due to the high associated expense and safety concerns, sticker chain was not used. Corrugated belting would hold the stalks loosely and would need an elaborate conveyor system. For these reasons it was also not used for this preliminary study. Instead, a spring-loaded positive grip cup that consistently held a variety of stalk sizes in an upright position for stripping was used.

3.2.3 Leaf Orientation

Initial testing indicated that the most effective stripping occurred when the leaves were oriented away from the direction of travel of the plant (Figure 3.3). This allowed the leaves to be cut close to the stalk before the lamina was shredded. Casada et al. (1976) showed that the force required to detach leaves from stalks was least when applied in a direction radial to the stalk at a point along the stem 1 in. away from the point of attachment. Once the leaves are directed backward, the sections of leaves to first encounter the strings are the stems or midribs at about a 1 in. [2.54 cm] distance from the stalk. This allowed for a clean removal with minimal force and very little leaf damage.

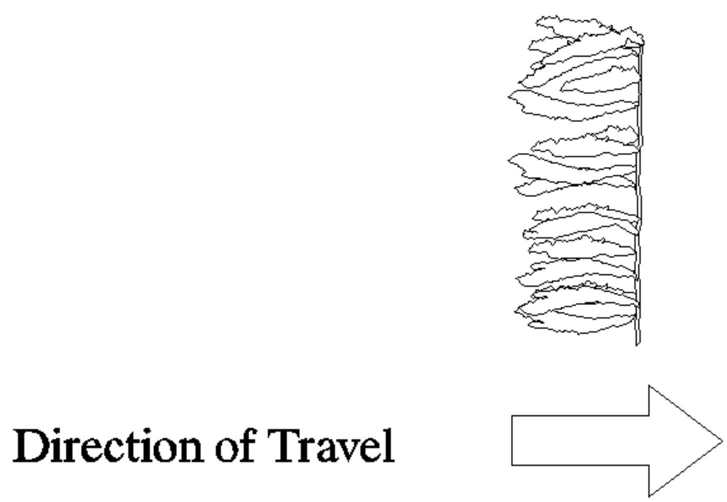


Figure 3.3: Leaves oriented opposite the direction of travel to optimize detachment by string trimmers.

Initially, push broom heads were used to brush the leaves in the desired direction. However, the stiffness of the bristles and the difficulty in mounting them at an opposed position led to the search for some different brushes. Straight bristle concrete smoothing brushes were chosen as a low cost, readily available, and easily mounted option. Once mounted opposed, the angle of the brushes on the horizontal plane was adjusted to funnel the plants toward the trimmers and brush the leaves back to optimize stripping (Figure 3.4).

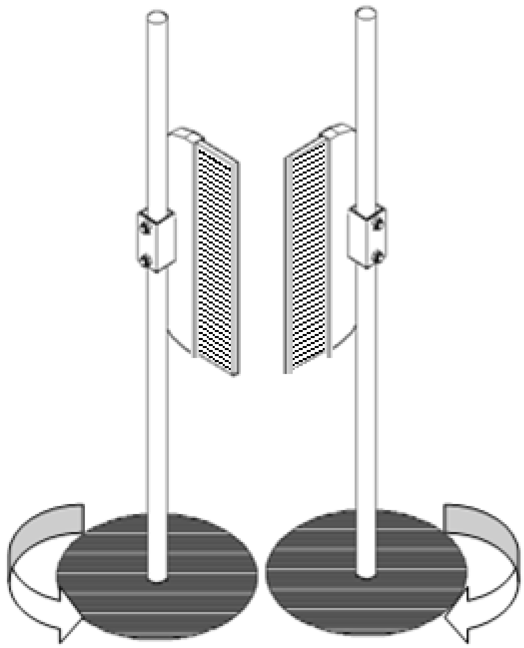


Figure 3.4: Brush setup which allowed for changes in brush angle.

From observation, more effective stripping occurred when the leaves were contained in the brushes as the trimmers cut them from the stalk. However, initial testing also showed that leaves cut while in the brushes remained in the brushes until the next plant pushed them out. The leaves being pushed out by the following plant tended to get pushed into the trimmer and thus somewhat shredded. It will thus be necessary to add a mechanism to eject the leaves from the brushes before the next plant enters the brushes. Several ways of accomplishing this are under consideration.

3.2.4 Leaf Removal

The main area of focus for the entire project was leaf removal. Initially, a relatively inexpensive Black and Decker (New Britain, CT) model ST4500 string trimmer was used. This trimmer came equipped with a single 0.065-in. [1.65 mm] line, a bump feed trimmer head and a 3.5-amp 10,000-rpm universal electric motor. Clamps were constructed to hold the trimmers so that plants held by the stripping wheel passed by the trimmer heads. Tests were conducted by orienting a single string trimmer head so that the cutting plane was parallel to the stalk and perpendicular to the direction of motion of the stalk (see Figure 3.5). The string length was 6 in. [15 cm] measured from the outer edge of the 4-in. diameter hub, which meant that the total cutting radius was 8 in. [20 cm]. Stripping efficiency was moderate and line wear was substantial after only attempting to strip a few plants. The 0.065-in. [1.65-mm] line was replaced with 0.105-in. [2.67-mm] line. The larger line was much less susceptible to wear, but introduced significant vibration and noise to the motor.

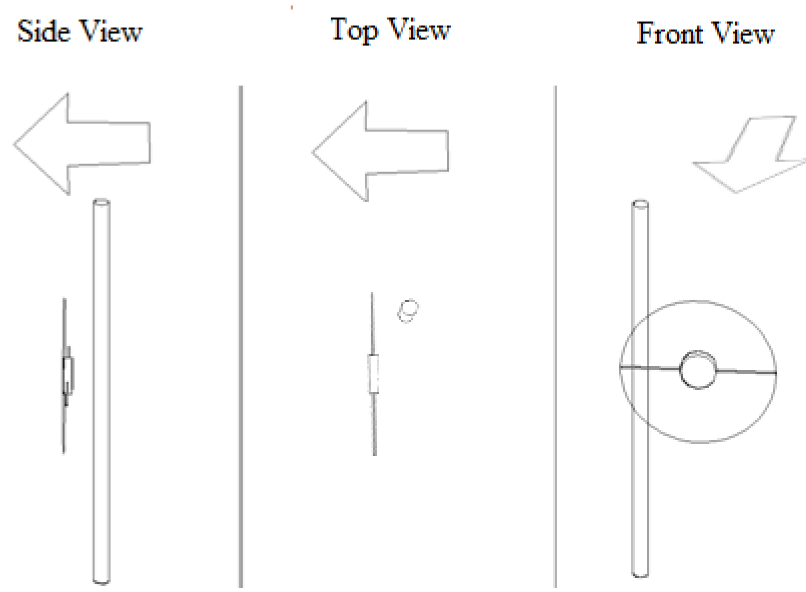


Figure 3.5: Stalk parallel to the cutting plane of the trimmer head and moving in the direction of the arrow.

Next, a configuration with two opposed trimmer heads was tested to maintain stripping efficiency while decreasing vibrations by running the motors slower. It had better results on leaf removal than the single trimmer head. Two line sizes of 0.065 in. and 0.105 in. [1.7 mm and 2.7 mm] were tested, and both had better leaf removal than the single trimmer head. However, greater coverage was required to strip an entire grade, and increasing the length of the string beyond 6 inches [15 cm] to get better coverage from a single line trimmer head caused a serious decrease in head speed and introduced major vibrations.

Flail blade heads were tried because they had the potential to reduce speed, thereby increasing motor life and possibly eliminating the need for brushes by reducing the shredding of the leaves. Testing of the flail cutters showed that at slow speeds, the flails did not fully extend and did not have enough momentum to cut the leaves. Furthermore, the flails were bent and the motors were stopped by the passing stalks. At fast speeds, the plants were mauled, cut in two or not stripped. Also, the coverage area of this type of trimmer was small; more flail heads and motors would be needed to achieve the same coverage area as the string heads.

A dual string head was tested to eliminate the unbalanced single line problem. At a string length of 7.5 inches [19 cm] measured from the outside of the 4 in. [10 cm] diameter hub (total 9.5 in. [24 cm] radius) and at maximum speed, the motor had little vibration. The dual string head on a single trimmer appeared to remove the leaves as efficiently as two opposed trimmers with single strings. Balancing the high speed motor has several advantages. It allows for longer strings to be used on the cutting head. For the single string head, as the string length increased the motor was unable to handle the unbalanced string mass; therefore, maximum string length was 5 to 6 inches [12 to 15 cm] from the hub. With the dual string head, the balanced mass allowed the string length to increase to 9 inches from the hub which gives an added benefit of a larger coverage area using only one trimmer head. Doubling the number of strings per head also doubled the number of string incidents per second striking the stalk, which potentially allowed for more efficient stripping at lower speeds.

Four strings on one trimmer head at 7.5 in. [19 cm] lengths (measured from the outside of the hub) were tried to increase the number of string incidents per plant. From observation, this worked slightly better than the dual string approach but significantly loaded the motor and decreased its speed. The strings were shortened to reduce the power requirement. At 5 in. [13 cm] lengths, a comparably high stripping performance occurred with the four string trimmer head when compared with opposed single string heads. The added stripping performance of the four string head, however, did not seem substantial enough to warrant the increased complexity of the trimmer head and the increased probability of foreign material in the tobacco from four instead of two strings. Thus, the use of a four string head was not pursued further for the stripping machine.

3.2.5 Grading and Coverage

Grading is a very important part of the stripping process because the grading affects the price per pound of the tobacco to be sold. Burley tobacco should be stripped into three or four grades to meet the demands of both domestic and export buyers. Stripping a plant into a single grade is relatively easy as demonstrated by several past machines; stripping into multiple grades is complex. The principle used for this project was grading by stalk position. A relatively accurate grading can be accomplished by removing a certain number of leaves from each section of the stalk. Preliminary testing showed that sharp edges of the cups holding the stalk damaged the string when trying to strip the lowest leaves. Therefore, for this machine concept, it was decided that the flying grade would first be removed by hand before the plant was placed in the machine. As the plant progressed through the machine, the lug grade would be removed, then the leaf grade and finally the tip grade. The mechanisms for the removal of each grade were spaced so that the stripped leaves fell into cardboard boxes below.

3.3 Final Experimental Configuration

All the information learned from the preliminary testing was reviewed to decide on an optimal configuration for initially testing the effectiveness of removing leaves with a string trimmer and ultimately the design of a complete machine.

Several key elements of the current experimental machine design were implemented (Figure 3.6). First, larger 0.105 in. [2.7 mm] string was required because the .065 in. [1.7 mm] line showed significant wear and broke frequently. Second, the 3.5 amp electric motor did not have enough power to turn the larger string at the speeds needed. A 6.3 amp universal electric motor (DAYTON model #2M145) was used to power the trimmer head. Third, a more readily adjustable setup was needed. All parts of the original machine were simplified and redesigned to contain needed adjustment points. The trimmer motor speed was controlled with a Dayton Electronics motor controller model #4X797, and monitored using a magneto-resistive Hall Effect sensor and a magnetic pulsar disc attached to the shaft of the electric motor. A program written in Microsoft Visual Studio was used to log motor speed over time. The logged data were used to examine changes in motor speed as plants passed the trimmer.

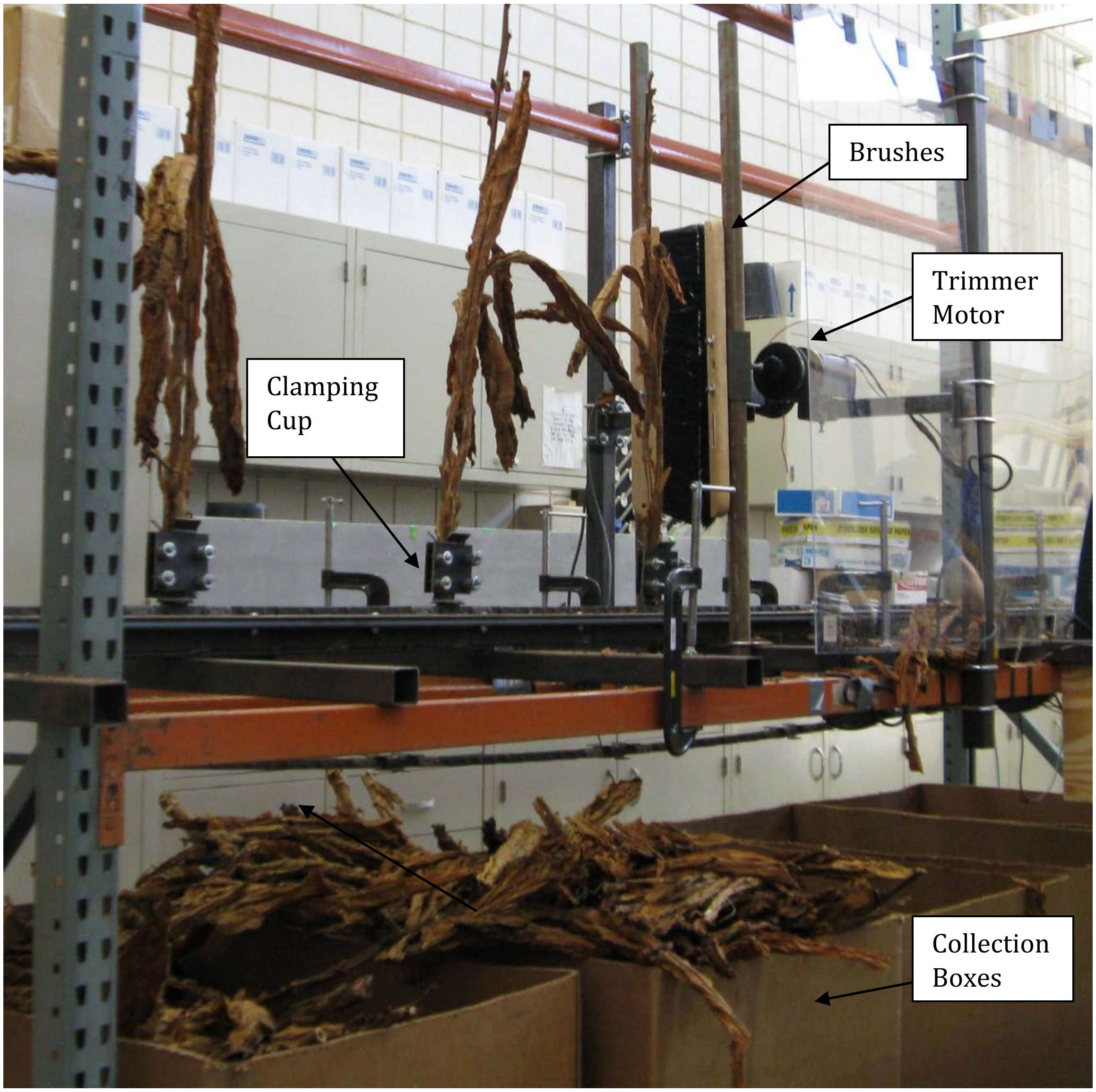


Figure 3.6: Configuration of the machine used for testing.

A 12-ft. [3.7-m] long straight line chain conveyor was chosen for the final design. This allowed for easier grading and alignment of the trimmer heads. The conveyor was constructed with two opposing track slots in which tabs on the chain moved. Horizontal legs were attached to the bottom of the conveyor so that it could be easily mounted inside a portable pallet rack setup. The conveyor was powered by a 1-Hp [0.76-kW] capacitor start electric motor through a gear reduction to obtain the proper speed and torque required for selected operation.

A spring-loaded self-centering positive grip cup that clamped a variety of stalk sizes was implemented on the machine (Figure 3.7). Only four cups were constructed and implemented at 24-in. [70-cm] intervals for the testing phase. The bottom of each cup was drilled, tapped and screwed directly onto tabs on the conveyor chain. Designs for loading and ejection mechanisms are being considered for the design of a field-scale prototype of the stripping machine but were not implemented at this stage.

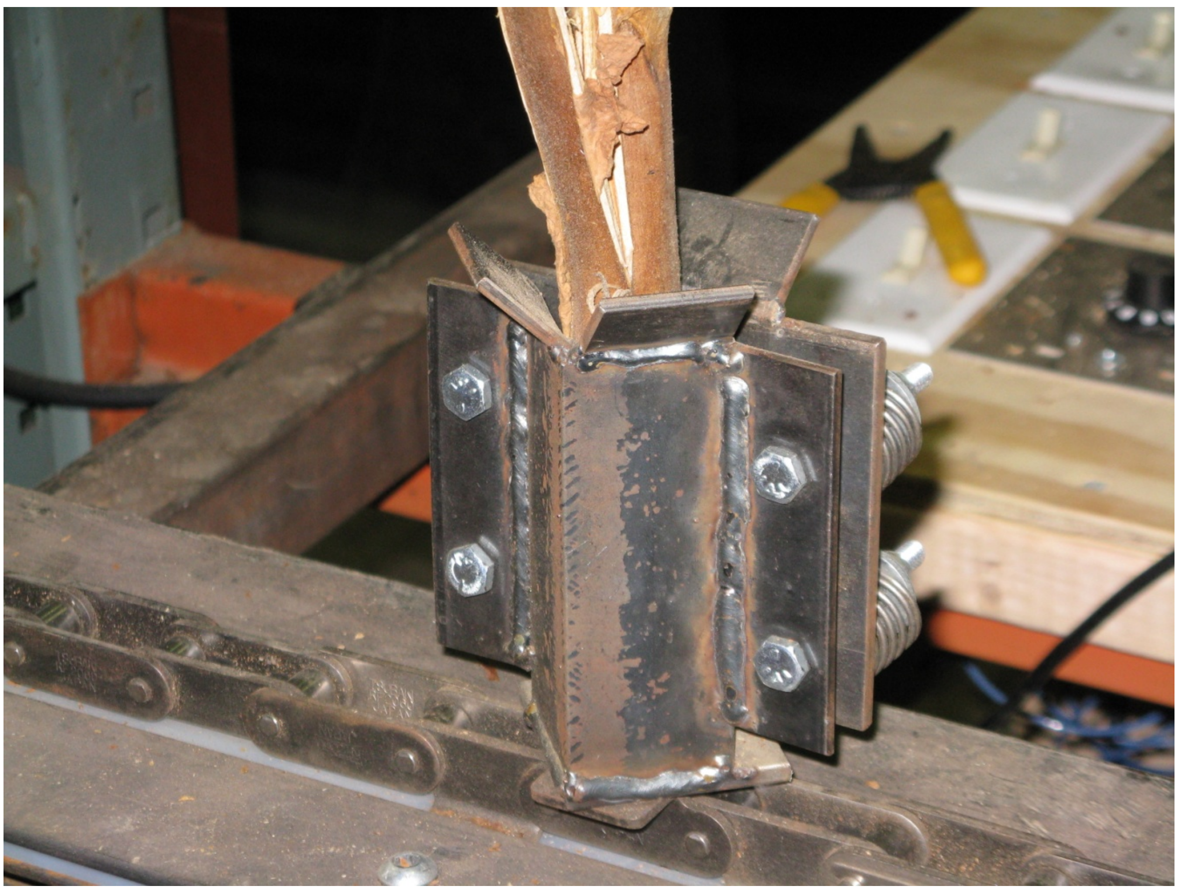


Figure 3.7: Spring-loaded cup for holding the tobacco plants.

Straight bristle concrete smoothing brushes were used in the final configuration based on positive results in preliminary testing. The brushes were mounted opposed on either side of the conveyor so that the bristles of one touched the bristles of the other. This brush configuration seemed to increase stripping efficiency in preliminary testing. The brushes were angled approximately 45 degrees along the length of the conveyor to funnel the leaves into the trimmer.

CHAPTER 4: EXPERIMENTAL METHODS

Based on preliminary testing observation, it was hypothesized that there is a speed threshold for optimum stripping of tobacco leaves from a stalk. Speeds above the threshold require more energy, contribute to increased string wear, and could cause excessive shredding of the leaves. Speeds lower than the threshold would not adequately strip leaves from the stalk. The speed thresholds for three different string lengths were investigated through experimental testing.

4.1 Geometric Analysis for Coverage

Assuming a typical burley tobacco plant contains 22 leaves per plant, the approximate breakdown for each grade would be as follows: three leaves for the flyings, seven for the lugs, seven for the leaf grade and five for the tip grade (Duncan et al. 2008). Assuming the leaves are nearly evenly space on the stalk, different grades take up a different length of the stalk as seen in Figure 4.1.

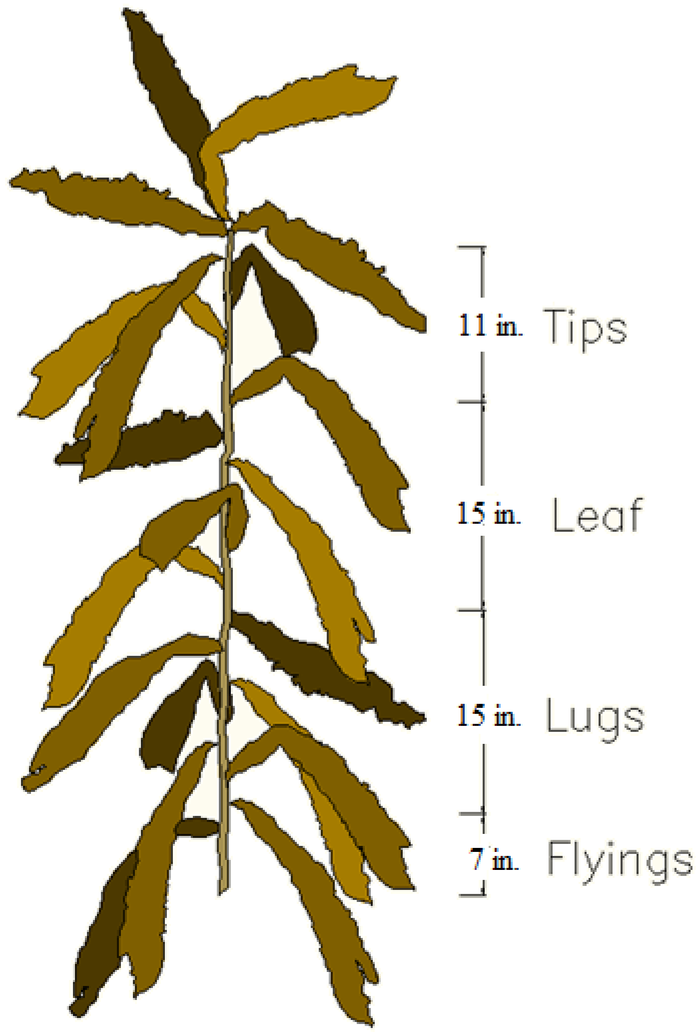
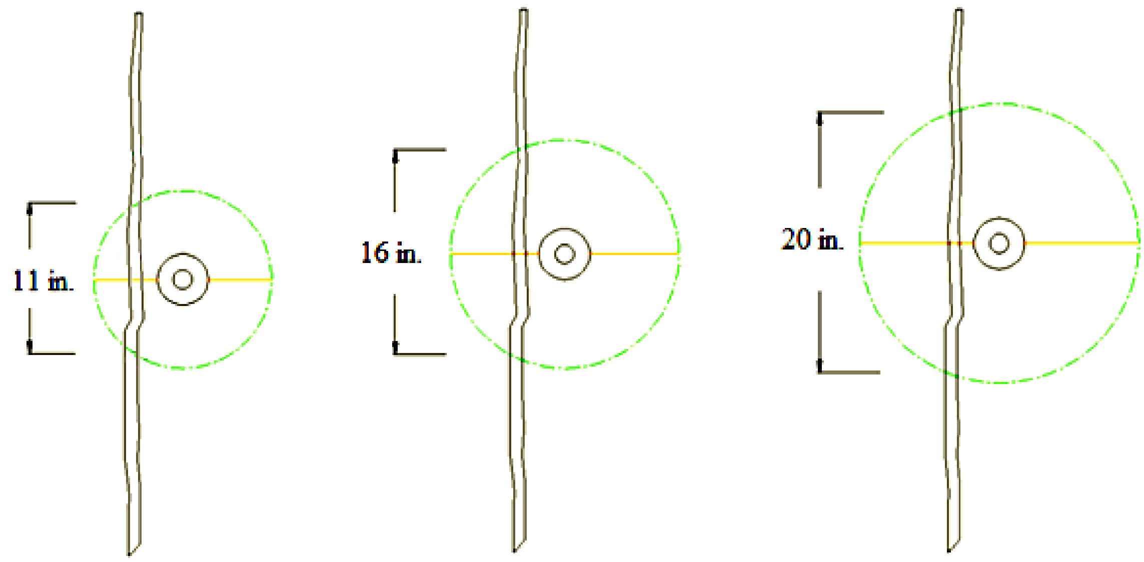


Figure 4.1: Four grade coverage for 48 in. plants.

Coverage of the entire tobacco plant and each individual grade by the trimmer strings was a major consideration for testing. Figure 4.2 illustrates the approximate length of stalk that each string length tested will cover, based on the distance from the center of rotation of the string to the stalk, which was about 4 inches [10 cm].



5 in. string (7 in. radius) 7 in. string (9 in. radius) 9 in. string (11 in. radius)

Figure 4.2: Stalk coverage length for different string lengths.

Taking the data from Figure 4.2 and arranging different string lengths for different grades in Figure 4.1 gives a fairly accurate grading of an entire stalk of tobacco based on stalk position. Overlapping the section of stalk stripped for each grade helps to ensure that all pieces of leaves are removed.

4.2 Speed Measurements and Recording

4.2.1 Bench Testing

Before implementing the speed sensors and the program to measure and log speed, the apparatus was tested in a more controlled environment. The 6.3 amp motor equipped with the magnetic pulsar disc was connected to a basic motor controller and the

Hall effect sensor was wired according to Figure 4.3. The sensor output was first observed on an oscilloscope to ensure correct wiring and functioning of the sensor.

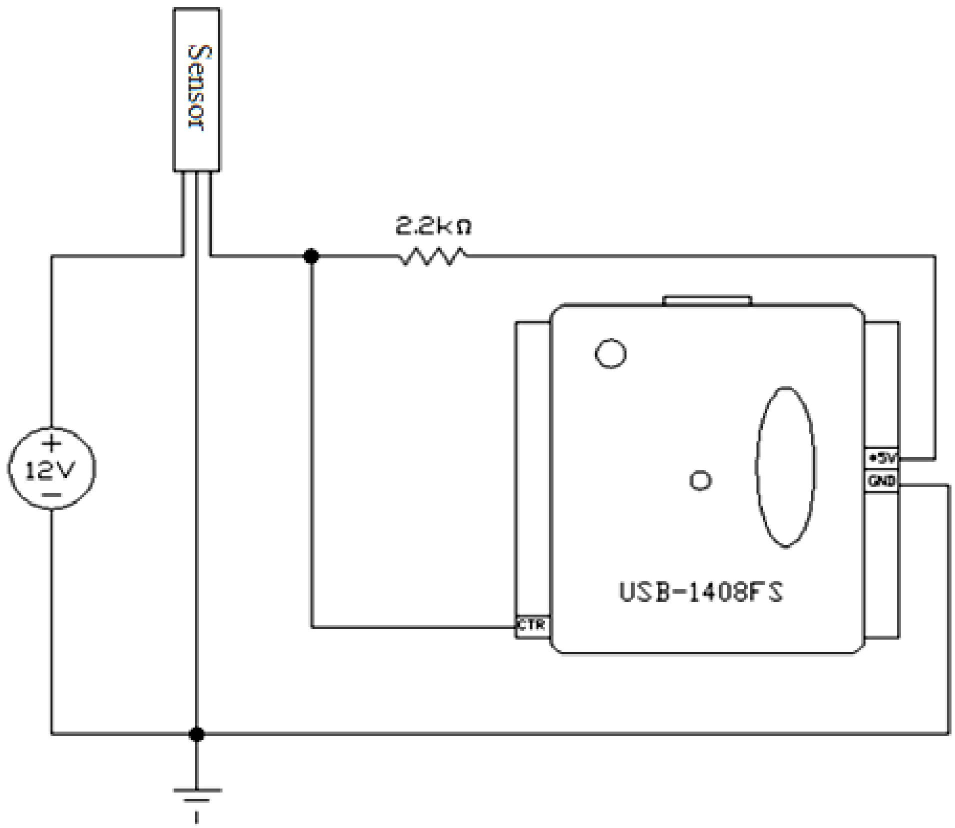


Figure 4.3: Circuit diagram for Hall effect sensor

A program was created in Microsoft Visual Studio to display and log speed over time. There were 20 magnets around the circumference of the disc and each produced one pulse. For one revolution of the motor, 20 pulses were generated. Knowing the geometry of the Pulsar discs, an equation relating pulses to speed was derived. Equation

1 shows an expanded version of how counts are converted into speeds. Counts are first converted into rotations, then to rotations per second and finally to rotations per minute. The program needed to measure the speed accurately at a fast enough sampling rate to capture abrupt speed changes. Both 250 ms and 500 ms were tested as appropriate time intervals. At the 500 ms sampling rate, the output was more stable, but the resolution in knowing the actual speed during abrupt changes was lower because fewer points were recorded. At the 250 ms sampling rate, more points were recorded and the resolution was higher, but the real time output was less stable. A sampling rate of 500 ms was chosen because it gave the best real time signal stability and an adequate number of points during abrupt speed changes.

$$Speed\ (rpm) = pulses \cdot \frac{1\ revolution}{20\ pulses} \cdot \frac{1}{0.5\ sec} \cdot \frac{60\ sec}{min} = 12 \cdot pulses \qquad (1)$$

The complete program code can be seen in appendix A. Both data acquisition boards were initialized and made ready for input. The program's stopwatch used to track the time was enabled. Its data were also used as the x-coordinates when graphing speed vs. time. The sample timer kept track of counts and recorded them when the timer got to 250ms. The program then converted the sampled counts to a speed reading, and displayed it on the computer screen in the dialog box. The calculated speed and stop watch readings were written to a .csv file. Finally, all the timers and counters were reset and the program saved and closed the file. From the logged data obtained from the program, a history of speed changes over time was logged to help better understand the dynamics of the motor when the trimmer head encountered an object.

4.3 Procedure for Single-Grade Stripping Efficiency Tests

When burley tobacco loses moisture it becomes very brittle and subject to handling damage. The effects of moisture loss in dry conditions can change the consistency of the leaves in as little as an hour. Dryer leaves tend to be easier to remove from the stalk but also tend to shatter in the process. To reduce the effect that the condition of the plants had on the performance of the stripping apparatus, the plants were stored in a controlled environment inside a conditioning chamber. The chamber was maintained at 20^{o}C and 80% relative humidity to keep the tobacco in case while not allowing it to mold in the moist air. Only the plants to be tested in the next hour were removed from the chamber. This method of storing the tobacco proved to be very effective in allowing an extended period of testing outside normal stripping times.

To make the experiments as controlled as possible, the first set of tests focused on only one leaf grade. The leaf and lug grades both make up the majority of the leaves on a tobacco plant. The leaf grade was chosen because it is closer to the top of the plant and is therefore more valuable. Furthermore, stripping it by machine while the stalk is held from the cut end proved to be more challenging in preliminary testing.

For each set of four plants, the leaf grade had to be isolated to ensure leaves from other grades would not affect the test results. Each plant was hand stripped to the nearest stem according to Table 1. Table 1 was created from the geometric analysis according to the expected coverage length known. The plants were then weighed separately on the scale shown in Figure 4.4. The four plants were placed in the four positive grip cups attached to the conveyor chain. The trimmer motor was started and the speed was adjusted to the desired test speed using real time speed indication from the logging program.

Table 1: Hand stripping ranges for different string lengths.

5 in. String	7 in. String	9 in. String
Strip first 14 in.	Strip first 12 in.	Strip first 10 in.
Leave 10 in.	Leave 14 in.	Leave 18 in.
Strip the rest	Strip the rest	Strip the rest

Table 2: String length and motor speed test combinations.

String length (in.)	Motor speeds (rpm)			
5	3000	3400	3800	4200
7	2800	3000	3200	3500
9	2200	2500	2800	3000

The speed data recorded were saved to a .csv file corresponding to the appropriate test number. After the four plants passed through the machine and the data logging was stopped, another weight measurement was taken to determine the amount of leaf removed by the trimmer.

Figure 4.4: Scale and platform used to weigh the tobacco plants.

The tobacco and stems remaining on the stalk were stripped by hand and the plant was weighed again. The procedure was repeated for four motor speeds associated with each length of string (see Table 2). The whole set of four tests was replicated three times. Note that in Table 2 each string length has a different range of test speeds. This was to compensate for shorter strings having a slower linear speed at the tip of the string.

The stripping efficiency for each motor speed and string length combination was calculated using Equation 3:

$$Stripping\ Efficiency = \frac{Initial\ Weight - Machine\ Stripped\ Weight}{Initial\ Weight - Hand\ Stripped\ Weight} * 100 \quad (3)$$

where the *initial weight* is the plant weight after the leaves surrounding the test grade were stripped, the *machine stripped weight* is the weight of the plant after it passed through the stripping machine and the *hand stripped weight* is the weight of the stalk after all remaining leaves and stems are removed.

4.4 Procedure for Three-Grade Stripping Efficiency Tests

Taking the information learned from the first set of tests, along with coverage and grading criteria from the geometric analysis, the machine was configured to accommodate the stripping of three grades by machine along with a fourth grade stripped by hand before feeding the machine. The same brush and motor configuration used on the single grade tests were installed in succession along the conveyor at different stalk heights, each height corresponding to a different grade. Optimal motor speeds were chosen for each string length tested in the single grade tests. The speeds chosen were based on the efficiency results of the single grade tests for each string length. The average stalk height of the plants used in testing was 44 inches [112 cm]. Based on simple geometry, each of the three stripping positions utilized 7 in. [18 cm] string lengths to achieve coverage for proper grading (Figure 4.5). For taller or shorter plants, the combination of string length and location for each grade could be changed.

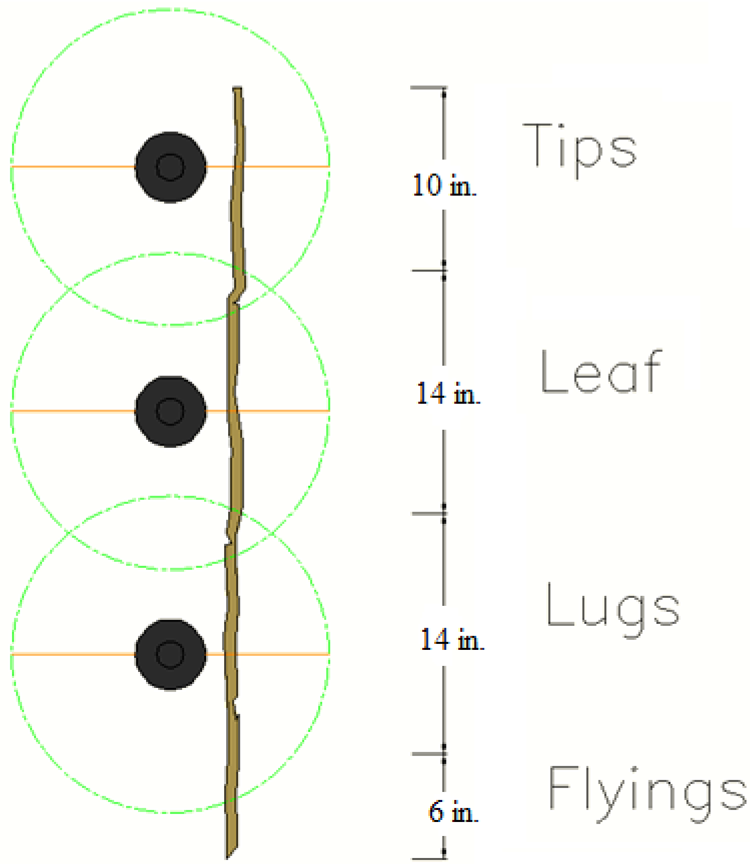


Figure 4.5: Three string coverage using 7 in. strings.

After the plants were removed from the conditioning chamber, the flying grade was removed from each plant by hand and the plant was weighed on the scale in Figure 4.4. Because adding the other two trimmers decreased the usable length on the conveyor needed for stationary loading of plants, only two plants were processed at a time. The plants were then passed through the machine where the lugs, leaf and tip grades were removed based on stalk position and linear progression though the machine (see Figure 4.6). After the plants passed by the three sets of trimmer heads, they were removed from the cup and reweighed. Then all the remaining leaf and stem material was stripped by hand and the plants were weighed again. An overall stripping efficiency was calculated for each plant using Equation 3. The process was replicated five times for 10 plants total. The stripping efficiency results for one plant seemed to be in error because it was greater than 100%, so it was left out. Note that no assessment was made of grading accuracy.

Figure 4.6: Three grades stripped by machine.

4.5 Proceduce for particle size analysis

Tests were conducted to determine the extent of shredding by the machine. While the size of the tobacco leaf pieces collected is not as much of an issue as it used to be because of new baling techniques, in order for the leaves to be recoverable, they need to meet certain size requirements. After consulting with an expert in the field to determine the cut-off size for collectable tobacco particles, a threshold 1 in. x 1 in. [2.5 cm x 2.5 cm] was chosen (B. Pearce, personal communication, 21 April 2010). Pieces larger than 1 in. x 1 in. [2.5 cm x 2.5 cm] were considered able to be baled and pieces smaller than that were considered losses.

When testing the stripping efficiency of the machine, some shredding was inevitable even after steps were taken to minimize it. It is important to note that with a contained stripping machine, most of the unrecoverable pieces from this test might in fact be recoverable. It is anticipated that very little tobacco would be lost outside of a fully working machine and thus, productivity would likely be higher than in these tests.

In previous testing, some shredding occurred as a plant passed the trimmer head and small tobacco pieces were thrown outward from the motor. To collect these flying pieces and ensure that all of the stripped leaf, shredded or whole, was collected, an enclosure of plastic sheathing was built around the leaf grade removal section of the tobacco stripping machine. The enclosure was open on the bottom and built in such a way that it funnelled the leaf particles to a sheet of 0.75 in. [1.9 cm] thick foam board for collection and inspection.

The same scale used in the previous testing was converted into a hanging scale by removing a plug on the underside of the device. A hook was attached and the scale was placed at about eye level on a single set of pallet racking shelves to accommodate tobacco hanging below it. A spring loaded wood clamp was purchased and fixed to the hook so that plants could be clipped to the scale for easy measurements (Figure 4.7).

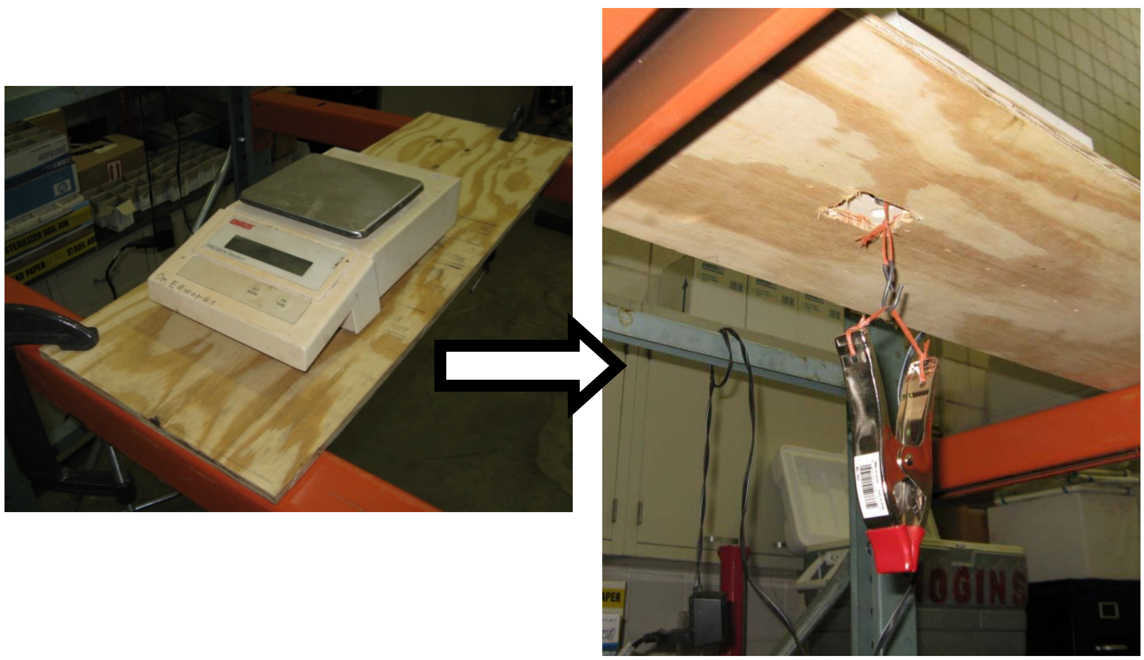


Figure 4.7: Plate scale converted into a hanging scale.

For each test, a tobacco plant was taken from the conditioning chamber, then all leaves except the leaf grade to be tested were stripped by hand according to Table 1. The plant weight was recorded from the hanging scale. The single plant was placed cut end first in a clamping cup on the conveyor and run through the plastic enclosure containing a trimmer. Since 3000 rpm for a 7 in. [18 cm] string length from previous testing gave the best stripping efficiencies, it was used as the appropriate speed for this phase of testing. The stripped stalk was removed and weighed again. All remaining leaf material left within the grade in question was removed by hand and the stalk was weighed again.

Pressurized air was used to blow leaf particles off the conveyor to ensure that all pieces were collected. Once all smaller particles were on the foam board, the stripped leaves remaining in the brushes were removed and added to the board. The leaves were sorted into three groups: whole leaves, pieces larger than 1 in. [2.5 cm] square and pieces smaller than 1 in. [2.5 cm] square. A photo was taken of each sorted group to ensure consistency in sorting (Figure 4.8). Each group of stripped leaf was individually weighed on the plate of the scale and recorded. The test was repeated for a total of 10 plants.

Figure 4.8: Sorting results from a particle size analysis test.

CHAPTER FIVE: RESULTS AND DISCUSSION

5.1 Statistical Analysis

A statistical analysis was conducted to determine if the differences in stripping efficiencies associated with different motor speed and string length combinations were significant. SAS was used to determine an appropriate model to test the interactions of the data collected for the single grade stripping efficiency tests. The P value returned from the SAS test was less than 0.0001 which indicated that the model selected was a good fit for the data (Table 10 of Appendix B). The *speed*, *length*, and the *speed*length* interaction all have a significant effect on stripping efficiency in this model (Table 3). All three respective P values are again less than 0.0001. This same model was previously run with both the trial day and replications per trial included to validate that neither a variance in days nor test conditions played a role in the stripping efficiencies. Neither of these had a significant effect on the model.

Table 3: ANOVA for speed and length interactions

Source	DF	Type III SS	Mean Square	F Value	Pr > F
spdLevel	3	11220.75727	3740.25242	14.71	<.0001
length	2	6362.45949	3181.22974	12.51	<.0001
length*spdLevel	6	8276.71897	1379.45316	5.42	<.0001

To refine the results of the ANOVA and determine the degree of significance of each interaction, a Tukey adjustment was conducted on the means of the three trials for each speed and string length combination. This could potentially eliminate possible combinations that were not good enough for the quality of stripping desired. The acceptable cutoff in stripping efficiencies was considered to be 90%. The results of this test are listed in Tables 11 and 12 of Appendix B.

There are two distinct groupings that are evident in the comparisons. Group one consists of 5-1, 5-2, 9-1 where the first number is the string length and the last is the motor speed ranking for that string length. Group two consists of all the others. P values of less than 0.001 indicate that there is a statistical difference between group one and two. Comparing members within each group with other members of the same group resulted in P-values of greater than 0.001 and thus, no significant differences within groups. The statistical differences separating group one from group two showed that the three motor speed combinations of group one are unacceptable if average stripping efficiencies of over 90% are desired. The statistics fail to narrow the results further; therefore, the results were analyzed more directly.

5.2 Single Grade Stripping

Four motor speeds for each string length were tested to pinpoint which speed/string combination gave optimal stripping efficiency for the tests run. Tables 4, 5 and 6 summarize the efficiency results for each of the three string lengths.

Table 4: Stripping efficiencies with standard deviations for 5 in. string length.

	Initial Motor Speed (rpm)			
	3000	3400	3800	4200
Trial 1	45.9	74.4	92.0	96.7
Trial 2	73.4	42.2	91.8	91.6
Trial 3	62.1	66.2	94.8	84.8
Efficiency	60.5%	60.9%	92.9%	91.0%
STDV	22.8	28.8	7.1	11.4

Table 5: Stripping efficiencies with standard deviations for 7 in. string length.

	Initial Motor Speed (rpm)			
	2800	3000	3200	3500
Trial 1	86.4	95.2	91.0	84.8
Trial 2	96.1	97.2	96.4	93.2
Trial 3	82.6	94.7	91.7	92.3
Efficiency	88.4%	95.7%	93.0%	90.1%
STDV	9.5	2.0	7.7	11.0

Table 6: Stripping efficiencies with standard deviations for 9 in. string length.

	Initial Motor Speed (rpm)			
	2200	2500	2800	3000
Trial 1	68.5	95.5	95.8	99.3
Trial 2	79.1	92.3	97.0	96.2
Trial 3	53.3	94.2	95.2	95.6
Efficiency	67.0%	94.0%	96.0%	97.0%
STDV	28.5	5.4	2.6	1.9

In Tables 4, 5 and 6 the average standard deviations (STDV) for 12 total plants, four plants for each initial motor speed and trial, were calculated. The lower the standard deviation for each motor speed string combination the better the consistency in stripping performance. Based on the overall averages from the set of tests, the standard deviations, and ruling out group one from the statistical analysis, the optimal motor speeds for each prospective string length were chosen (Table 7).

Table 7: Optimal speeds for each string length.

string length (in.)	optimal motor speed (rpm)
5	3800
7	3000
9	2800 or 3000

Notice that for a string length of 9 inches [23 cm], both 2800 and 3000 rpm are listed in Table 7. Both motor speeds resulted in high stripping efficiencies. Based solely on stripping efficiency, the optimal speed to run a trimmer with a 9 in. [23 cm] string would be 3000 rpm. However, running the motor an extra 200 rpm might not warrant the relatively small gain in stripped leaf weight when compared with an increased chance of tobacco contaminated with plastic foreign material from string breakage. Under the conditions observed during all three tests, string wear and breakage seemed to be minimal. With more extreme conditions or with a large quantity of plants being run through the machine this could become an issue.

5.3 Three Grade Stripping

Based on the procedure from section 4.4, three-grade stripping efficiencies were calculated for entire plants. An overall efficiency for the entire group was also calculated to give an estimate of the performance of the machine over a set of plants (Table 8).

Table 8: Results for full plant stripping efficiency.

Plant	Efficiency (%)	Average Efficiency
1	94.6	97.0%
2	98.0	
3	94.1	
4	98.3	
5	96.7	
6	97.8	
7	98.0	
8	99.8	
9	95.8	
Note: The stripping efficiency results for plant 10 contained an error and were left out.		

The overall efficiency of 97% confirmed that the stripping efficiency of the machine remained high after the single grade stripping tests were expanded to cover multiple grades on an entire plant. These results validate the potential this machine has to be a benefit to smaller scale burley tobacco growers who primarily utilize hand labor. However, further testing would be required to assess grading accuracy.

5.4 Particle Size Analysis

The results from the particle size analysis tests show an average stripping efficiency of 96.9% for stripping of the leaf grade in this set of tests. The consistency of these stripping results compared with the results for the single grade 7 in. [18 cm] string length tests helps justify that the distribution of tobacco leaf piece sizes measured are typical values that could be observed over a large number of plants. Table 9 shows the percentage of the total weight of each sorted size category. Leaf pieces 1 in. x 1 in. [2.5 cm x 2.5 cm] and smaller made up 5.6% of the total weight. As discussed in the procedures, some of these could potentially be lost if proper measures are not taken to collect all leaf fragments. As long as these smaller pieces fall into the boxes below, the smallest pieces should be imbedded in the mix of other fragments. Thus, the loss of the smaller fragments could be small.

Table 9: Sizes of tobacco leaf pieces after being stripped by machine.

Plant		Stripping Efficiency (%)	Whole Leaf Particles (%)	Particles larger than 1x1 in. but smaller than whole leaves (%)	Particles 1x1 in. and smaller (%)
1		97.6	81.8	6.2	11.9
2		95.7	91.6	3.5	4.9
3		92.5	95.5	1.9	2.5
4		99.3	89.5	3.5	7.0
5		97.2	89.7	4.5	5.8
6		99.8	89.7	5.0	5.3
7		99.7	91.9	3.4	4.7
8		93.9	93.4	3.1	3.5
9		94.8	91.3	4.3	4.3
10		98.4	86.5	7.3	6.1
Average		96.9%	90.1%	4.3%	5.6%

5.5 Graphical Motor Speed Analysis

5.5.1 Visual Analysis

All recorded speed data were graphed to try to understand and explain the reasons for low and high stripping efficiencies. Figure 5.1 is a representative graph corresponding to the processing of four tobacco plants that resulted in a relatively low stripping efficiency. It shows the trimmer motor speed versus time for replication three of the single grade efficiency tests for an initial motor speed of 2200 rpm and a 9 in. [23 cm] long string. The four major troughs of the graph show the points at which the motor has slowed to its minimum speed due to each of four tobacco plants passing by the trimmer heads and being stripped. Note the ample resolution in outlining the abrupt speed changes evident by the multiple data points at each major inflection.

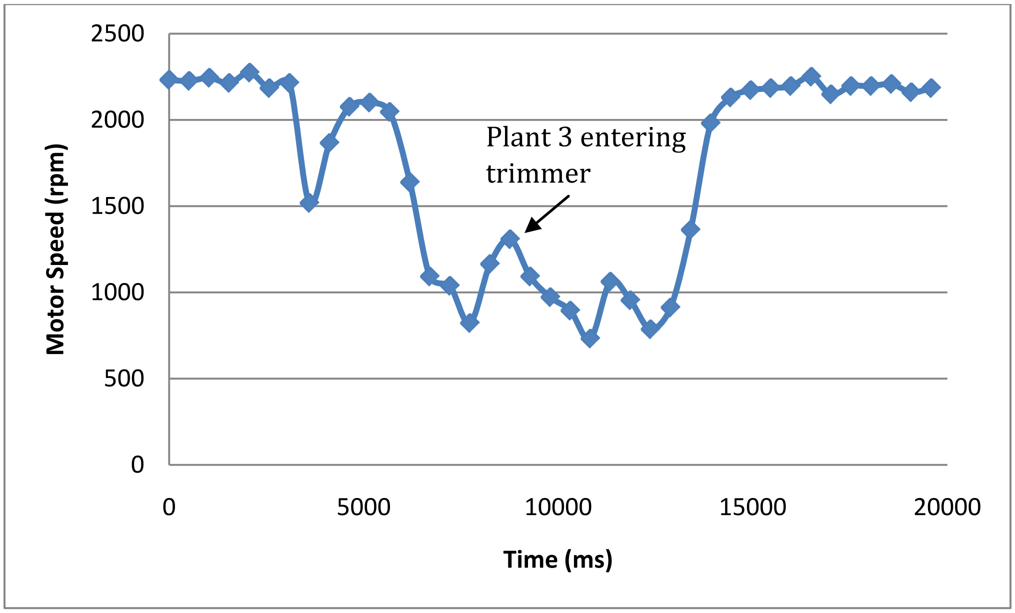


Figure 5.1: Motor speed versus time for an initial motor speed of 2200 rpm with string length of 9 in.

The speed of the trimmer head never recovered to its initial speed between plants. As the third plant encountered the trimmer, the motor speed is around 1200 rpm. Since each test was run with four plants to get a better representation of average stripping efficiency, when one plant was not stripped appropriately due to inadequate motor speed, the efficiency for the entire test was adversely affected. In this instance the motor speed failed to recover, and plants three and four enter the strings that are spinning significantly slower than intended. Looking at the initial data that went into Tables 4, 5 and 6, plant one had a stripping efficiency of 88% and plant two had an efficiency of 85%, but plants three and four had efficiencies of only 14% and 26%, respectively. This is why the average stripping efficiency for this test was only 53.5%. It seems that the initial trimmer motor speed was sufficient to effectively strip the first plant or two, but not consecutive plants at 24 in. [61 cm] spacing and with a conveyor speed of 0.73 ft/s [22 cm/s]. It is important to note, however, that the conveyor speed was arbitrarily chosen, and that none of the stripping efficiency tests were concerned with conveyor speed. Slowing the conveyor down could improve efficiency by allowing the motors running at slower speeds to recover between plants.

Figure 5.2 is a representative graph for a test resulting in a high stripping efficiency of 97%. It shows the trimmer motor's speed versus time for replication two of the single grade efficiency tests for an initial motor speed of 2800 rpm and a 9 in. [23 cm] long string. Again each slope change represents a plant moving past the string trimmers. In this test, the motor appears to have sufficient power to recover before encountering the next plant. As the next plant reaches the trimmer, the motors are spinning at almost the initial speed. This leads to a high stripping efficiency for each plant and thus a high average efficiency. Individual plant stripping efficiencies for plants one through four of this test were 96%, 99%, 96% and 98%, respectively. The optimal feed rate is one where the next plant arrives just as the motors have recovered nearly to the initial speed.

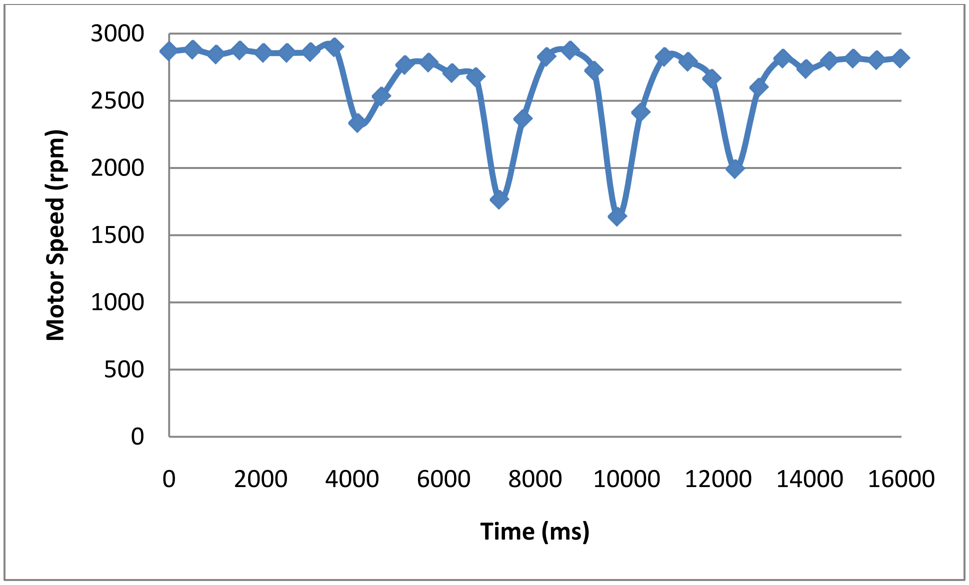


Figure 5.2: Motor speed versus time for an initial motor speed of 2800 rpm with string length of 9 in.

5.5.2 Energy Approximation Analysis

The data recorded from the stripping efficiency tests were analyzed to determine the amount of energy required to strip plants at different initial motor speeds. This could potentially help with selecting the optimal operational speeds and machine parameters based on energy usage. Ideally, meters would have been placed on the inputs to the trimmer motors to measure power during stripping, but since this was not done, the speed versus time graphs were analyzed from time t_0 (just before encountering a plant) to time t_f (the instant the motor fully recovers after the last plant) in an attempt to approximate energy usage. At t_0 the trimmer motor had torque, T_M. T_M is created by the electric current and balances the external torques due to friction and wind resistance. This external non-plant related torque was assumed to be constant throughout the tests and was, therefore, ignored in the analysis.

When the trimmer encountered a plant, the force of the strings on the leaves caused a torque on the motor that opposed rotation. The torque caused by the plant, T_P, had a negative value because it worked against the motor. The net torque during deceleration is $(T_M - T_P)$. After the plant was clear of the trimmer head, the motor was accelerated by the torque of the motor toward its initial speed. Since the plant torque no longer had an effect on the motor, the net torque for acceleration was T_M.

Due to an unbalance of torques, it was hypothesized that the average magnitude of the decelerations (negative slopes) would always be slightly greater than the average magnitude of the accelerations (positive slopes). Including all plants in the time frame t_0 to t_f, the difference between the averages of the negative slopes and positive slopes should give the difference in angular acceleration caused by a total of four plants.

Knowing that:

$$\propto = T/I \qquad (4)$$

where

I = Moment of inertia of the motor, trimmer head and pulsar disk

$\propto$ = The angular acceleration or deceleration of the motor (slope)

the difference in slopes is

$$\propto_1 - \propto_2 = \frac{(T_M - T_P)}{I} - \frac{(T_M)}{I} \rightarrow \propto_1 - \propto_2 = \frac{-T_p}{I}. \qquad (5)$$

Therefore

$$T_{net} = \left(\frac{-T_p}{I}\right) * I \rightarrow -T_p \qquad (6)$$

Figure 5.4 shows the average difference in acceleration of the motor for each of the trials for the string length-motor speed combinations tested. Each vertical grouping of points represents three replications for a specific string length and motor speed combination. Because the points for each vertical grouping greatly differ, it was concluded that there was no correlation between initial motor speed and associated difference in angular acceleration. Thus, the initial motor speed does not affect the size of the torque exerted by the plants. The torque exerted by the plants, T_P, could be affected by the size of the stems, the case of the leaves, the variety and the grade being stripped.

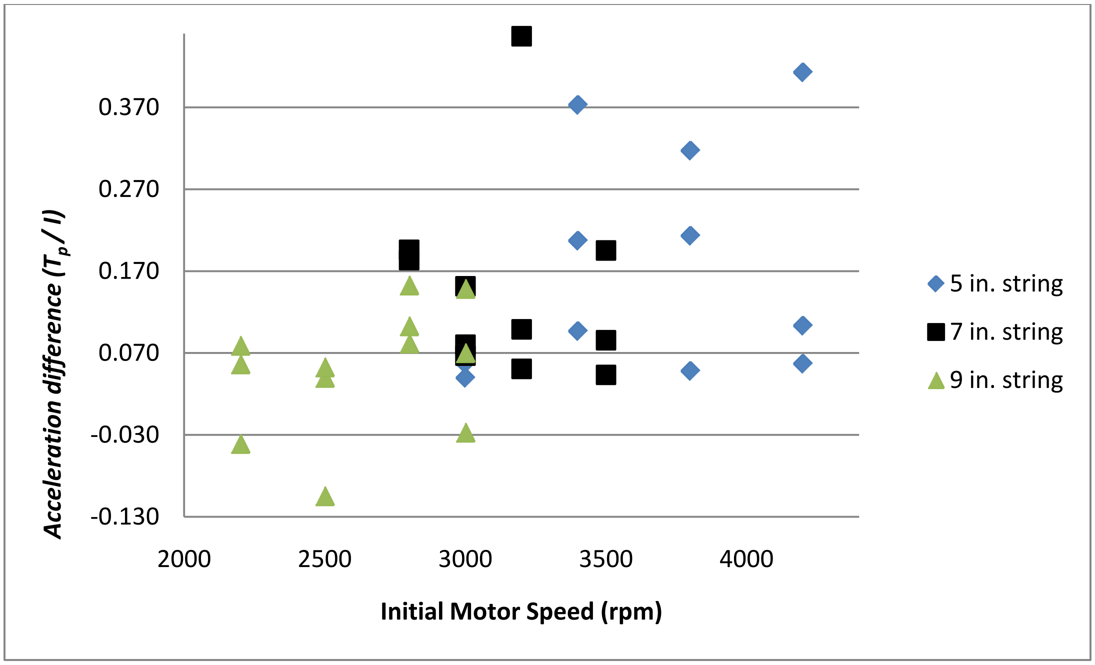


Figure 5.3: Acceleration difference (T_p/I) for all of the motor speed and string length combinations.

The values ranged from -0.104 to 0.457 rpm/s with an average value of 0.117 rpm/s (appendix B). Since the results vary greatly and were considered inconsistent, they were not accurate enough to generate a useful energy requirement calculation. However, the energy used by the system could be obtained from the general energy equation based on the number of revolutions of the motor:

$$E = W = T_{net} * \Delta x \quad (7)$$

where

W = Work done by four plants

Δx = the total number of revolutions from t_0 to t_f

Since the area under a speed versus time graph is the displacement, calculating the area under each motor speed versus time graph will give the total number of revolutions turned during each test. As stated before, the initial motor speed does not affect torque, but it does directly influence work done on the motors. Higher initial speed means a greater angular displacement of the trimmer heads, Δx, and a higher energy usage.

The visual analysis from section 5.5.1 showed that the initial speed also affects the recovery of the motors and thus the angular displacement of the trimmer head. To find an optimal speed to run the motors based on an energy analysis, both a more detailed measurement/calculation of energy and visual inspection of the dynamics of the trimmer head are needed.

5.6 Productivity and Economic Considerations

To determine potential productivity of the stripping machine, the speed of the conveyor was calculated. A stop watch was used to measure the amount of time for a cup to travel 147 inches [373 cm] (the length of the machine from the outside of each upright). For two different trials timed, 16.88 and 16.73 seconds were recorded. A linear conveyor speed of 0.729 ft/s was calculated. Knowing that the cups are spaced 24 [61 cm] inches apart, 2.73 s/plant was determined.

Hand stripping the flyings was practiced and timed on two sets of five plants. From the numbers, a conservative estimate for a single person to hand strip and feed the machine would be 1 plant every 6 seconds. If the conveyor speed of 2.73 s/plant is slowed down slightly to 3.0 s/plant, then two people hand stripping flyings could feed the machine (each person feeding plants alternately).

Two people feeding the machine (at a rate of 2 plants/6s) results in a productivity of approximately 1,200 plants/hr. If all cups are filled and the machine runs for eight hours with no malfunctions or stops, the machine would be 100% efficient and the estimated would be around 1200 plants/hr. At 7,000 plants/ac [17,500 plants/ha], an acre of tobacco could be stripped in 5.83 hours, and the productivity would be 1.37 ac/day [0.55 ha/da]. Depending on the yield, and assuming a four person crew (with two workers for exchanging collection boxes and baling), the potential stripping rate with this machine would be around 100 lb/wkr•hr [45 kg/wkr•hr] or 23 wkr•hr/ac [58 wkr•hr/ha] for a yield of 2 lb [0.9 kg] per stick or 2333 lb/ac [2625 kg/ha

Assuming that the machine has a reasonable operating efficiency of around 75% due to slow downs caused by missed cups or broken trimmer lines, an estimate for the projected productivity would be around 900 plants/hr. The machine could strip 300 lb/hr [135 kg/hr] for a total 2,400 lbs [1,080 kg] of tobacco for an eight hour day. This would be a capacity of around 1.0 acre [0.41 ha] stripped per day, depending on yield. With a four person crew the labor rate would be about 32 wkr•hr/ac [80 wkr•hr/ha]. Typical hand stripping requires 50-75 wkr•hr/ac [125 to 188 wkr•hr/ha] (Duncan, 2006c), so this stripping machine has the potential to reduce labor by at least 18 wkr•hr/ac [45 wkr•hr/ha] over the conventional system.

Labor costs for a crew of workers can range from $10 to $15 per hour depending on location and housing costs. A farmer using a stripping machine based on this concept on 20 acres [8 ha] of tobacco could potentially save $3,600/year in labor costs over conventional hand stripping methods at a labor rate of $10/hr. At a labor rate of 15 $/hr, savings could be as high as $5,400.

A cost analysis for the stripping apparatus is shown in Appendix E. This analysis was based on actual materials and parts costs for the test set up as well as on projected materials and costs for a field-operable prototype. The fabrication costs were assumed to be equal to the materials and parts costs; in addition, the same amount was added on for overhead/profit. The estimated price for the machine was $13,167. At this price, the payback period for the machine would be two and a half to four years, depending on the labor rate.

CHAPTER SIX: RECOMMENDATIONS AND CONCLUSIONS

With results from three-grade testing showing an average of 97% efficiency in removing burley tobacco leaves from the stalk, the development of a low cost system to perform this task seems promising. Below are conclusions and recommendations for future testing and work on the development of a fully operational field prototype.

6.1 Cups

The cups described in chapter 3 were designed for the purpose of testing with this setup only. They performed very well throughout all phases of testing and allowed for the use of a wide range of stalk sizes while still holding each stalk firmly and in a vertical position. Inserting and removing a stalk from the spring loaded cups, however, was somewhat difficult. A modified version of this cup design will be needed for an operational stripping machine that allows workers to easily insert the ends of the stalks into the cups.

6.2 Brushes

The brushes used for testing worked well to aid in stripping and reduce leaf shredding. They were long enough to brush back an entire grade of tobacco, and were stiff enough to move and position the leaves behind the stalk during operation without damaging the leaves or bending the stalk. With the setup used, leaves removed from the previous plant would stay lodged between the set of opposed brushes. This did not seem to affect the operation of the brushes, but did affect the functioning of the trimmer heads. On occasion, leaves tangled in the brushes would be knocked into the path of the trimmer head by the next plant. This caused noticeable shredding and, depending on the number of leaves in the brushes, a decrease in trimmer head speed and thus a lower stripping efficiency for the plant being stripped. Opening the brushes to allow the previous leaves to be ejected and fall into the appropriate bale boxes would be a way to modify the current design to improve the quality of leaf stripping achieved with the machine.

6.3 Grading

Grading for this concept can be considered in two parts: how effectively the leaves are removed from each region of the stalk as it passes through the machine, and how well the leaves are funneled into the appropriate collection boxes after being removed from the stalk. As described in the geometric analysis in chapter three, the grading of the plant into sections based on stalk position and linear progression though the machine worked well. The trimmers were able to effectively remove the correct leaves from the leaf, lug and tip stalk positions on the plant for uniform stalk lengths. Removing the flyings by hand was demonstrated during testing to be an effective and simple way of preventing excess string wear.

For consistent plant sizes, the machine appears to be able to grade leaves appropriately. Grading inaccuracies arise when plants of vastly different heights are processed by the machine. Efficient stripping can still be achieved by overlapping grades and by extending the coverage length of the tip grade trimmer, but grading accuracy would be affected. With plants of moderately varying heights, this machine should have the ability to do as good of a job grading as any other semi-automated stripping machine.

Funneling the leaves into the appropriate collection boxes can also affect the proper final grading. The majority of the leaves stripped with this setup fell into the correct boxes. Leaves that hung in the brushes and were shredded tended to be dispersed by the trimmer and mis-graded. Shielding between each grade removal, exterior shielding to keep all leaf particles within the confines of the machine, and leaf ejection mentioned in the previous section should help minimize improper grading.

6.4 Conveyor Speed

It was theorized that if the motor speed drops too low before the next plant is encountered, the stripping efficiency for the subsequent plant may be reduced. Analysis has shown that the time required for the motor to regain its initial speed has an effect on the overall stripping efficiency. A potential solution to examine would be increased plant spacing, slower conveyor speed or more powerful motors. Examining graphical data like that in section 5.5 could help to calculate the required plant spacing or the needed speed of the conveyor.

6.5 Power Requirements and Usage

During the course of testing and analysis it became evident that a current meter on the input to the electric motors would have been useful to show energy usage by the electric trimmer motors. Knowing the current, i, and the voltage, v (which was 115VAC), power, P, could have been calculated from $P = i \cdot v$. Energy could also have been calculated from $P = W/\Delta t$, where W is work and Δt is the duration of the test. It would have been useful to compare energy and speed to further justify the optimal stripping motor speeds. It would have also been useful to do an energy and cost analysis for the different string lengths of each motor speed. This could be very helpful in determining potential savings for different electric motor combinations that would be in operation for up to several hundred hours each stripping season.

6.6 Conclusion

The machine performed well during testing to determine an optimal setup for leaf removal and grading. The data showed that there was a significant difference in stripping efficiency for faster speeds at a given string length. Results for three-grade stripping (with the fourth grade stripped by hand) showed an average stripping efficiency of 97%. Making several modifications to the current design of the machine to:

1. eject leaves from the brushes to reduce potential losses due to shredding
2. help funnel the leaves into the appropriate bale boxes,
3. Improve machine loading and stalk ejection at the ends of the conveyor and,
4. monitor power usage to increase motor life and decrease costs

should advance the current machine into an operational field prototype. Implemented on a full scale four grade basis, this stripping machine could result in a savings of at least 18 wkr•hr/ac [45 wkr•hr/ha]. This would be a remarkable reduction in the labor required to produce an acre of tobacco, a huge savings to the producers and a step forward for the burley tobacco industry.

APPENDIX A

```
'******************************************************************
'* Title: Stripping Project                                       *
'* References: MccDaq                                             *
'*                                                                *
'* Date: 1/20/10                                                  *
'* Description: This program reads the counts from 2 sensors,     *
'*          converts them to RPM, and is able to store the        *
'*          RPM over time in an excel file.                       *
'*                                                                *
'******************************************************************

Public Class Main

    Private DAQ1 As New MccDaq.MccBoard(1)  'Define DAQ as a global MccBoard object so it's
accessable to any function in the Main class, initialize the DAQ as board #1.
    Private DAQ As New MccDaq.MccBoard(0)  'Define DAQ as a global MccBoard object so it's
accessable to any function in the Main class, initialize the DAQ as board #0.
    Private SWatch As New Stopwatch

    '***** This subfunction is automatically called when the program loads *****
    Private Sub Main_Load(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles
MyBase.Load

        Sample.Enabled = True   'Enable the timer which samples the USB-1408FS digital inputs every 500
milliseconds.

    End Sub

    '***** This subfunction is called every time the sample timer reaches a <interval> *****
    Private Sub counter(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles
Sample.Tick
        Dim Number As Integer 'Variable used to store a 4-bit number
        Dim Number1 As Integer

        Sample.Enabled = False
        DAQ1.CIn32(1, Number1)
        DAQ.CIn32(1, Number)
        DAQ1.CLoad32(MccDaq.CounterRegister.LoadReg1, 0)
        DAQ.CLoad32(MccDaq.CounterRegister.LoadReg1, 0)
        Sample.Enabled = True

        Number1 = Number1 * 6       'Needs to be 12 if using 250 ms
        TextBox2.Text = Number1

        Number = Number * 6        'Needs to be 12 if using 250 ms
        TextBoxCount.Text = Number

        If Button1.Text = "Stop File" Then

            SWatch.Start()
            My.Computer.FileSystem.WriteAllText(SaveFileDialog1.FileName,
SWatch.Elapsed.TotalMilliseconds.ToString + "," + Number.ToString + "," + Number1.ToString +
vbCrLf, 1)
        End If
```

```
   End Sub
   Private Sub Button1_Click(ByVal sender As System.Object, ByVal e As System.EventArgs) Handles
Button1.Click
      If Button1.Text = "Save File" Then
         Try
            SaveFileDialog1.ShowDialog()
            My.Computer.FileSystem.WriteAllText(SaveFileDialog1.FileName, "Time,Speed,Speed 1" +
vbCrLf, 0)
            Button1.Text = "Stop File"

         Catch ex As Exception

         End Try

      Else
         Button1.Text = "Save File"
         SWatch.Reset()
      End If



   End Sub

End Class
```

APPENDIX B

Table 10: Anova to determine goodness of fit of the model.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	25861.54809	2351.04983	9.24	<.0001
Error	131	33316.54936	254.32480		
Corrected Total	142	59178.09745			

Table 11: Tukey mean calculation for string length and speed combinations.

length	spdLevel	effic LSMEAN	LSMEAN Number
5	**1-L**	60.4601039	1
5	**2-ML**	60.9396513	2
5	**3-MH**	92.8800084	3
5	**4-H**	91.0293608	4
7	**1-L**	88.3728770	5
7	**2-ML**	95.7119331	6
7	**3-MH**	93.0679686	7
7	**4-H**	90.0919491	8
9	**1-L**	66.9975857	9
9	**2-ML**	93.8283476	10
9	**3-MH**	95.9947009	11
9	**4-H**	97.0297047	12

Table 12: Tukey comparison of the mean of string length and speed combinations.

Least Squares Means for effect length*spdLevel
Pr > |t| for H0: LSMean(i)=LSMean(j)

Dependent Variable: effic

i/j	1	2	3	4	5	6	7	8	9	10	11	12
1		0.9414	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	0.3172	<.0001	<.0001	<.0001
2	0.9414		<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	0.3538	<.0001	<.0001	<.0001
3	<.0001	<.0001		0.7767	0.4900	0.6643	0.9770	0.6692	0.0001	0.8869	0.6332	0.5250
4	<.0001	<.0001	0.7767		0.6839	0.4733	0.7547	0.8857	0.0003	0.6748	0.4470	0.3584
5	<.0001	<.0001	0.4900	0.6839		0.2617	0.4721	0.7922	0.0013	0.4140	0.2439	0.1859
6	<.0001	<.0001	0.6643	0.4733	0.2617		0.6853	0.3896	<.0001	0.7777	0.9654	0.8399
7	<.0001	<.0001	0.9770	0.7547	0.4721	0.6853		0.6484	0.0001	0.9092	0.6538	0.5439
8	<.0001	<.0001	0.6692	0.8857	0.7922	0.3896	0.6484		0.0005	0.5756	0.3663	0.2886
9	0.3172	0.3538	0.0001	0.0003	0.0013	<.0001	0.0001	0.0005		<.0001	<.0001	<.0001
10	<.0001	<.0001	0.8869	0.6748	0.4140	0.7777	0.9092	0.5756	<.0001		0.7454	0.6314
11	<.0001	<.0001	0.6332	0.4470	0.2439	0.9654	0.6538	0.3663	<.0001	0.7454		0.8739
12	<.0001	<.0001	0.5250	0.3584	0.1859	0.8399	0.5439	0.2886	<.0001	0.6314	0.8739	

APPENDIX C

Table 13: Results of dynamic analysis.

Test Repetition	String Length (in.)	Motor Speed (rpm)	Positive Slope (rpm/s)	Negative Slope (rpm/s)	Difference (rpm/s)	Ratio
1	5	3000	0.395	0.452	0.057	0.874
2	5	3000	0.168	0.208	0.040	0.809
3	5	3000	0.232	0.313	0.081	0.742
1	5	3400	0.438	0.534	0.097	0.819
2	5	3400	0.397	0.770	0.373	0.516
3	5	3400	0.339	0.547	0.207	0.621
1	5	3800	0.482	0.530	0.048	0.909
2	5	3800	0.299	0.513	0.213	0.584
3	5	3800	0.348	0.665	0.317	0.523
1	5	4200	0.661	0.718	0.057	0.921
2	5	4200	0.260	0.363	0.103	0.715
3	5	4200	0.327	0.740	0.413	0.442
1	7	2800	Error	Error	Error	Error
2	7	2800	0.411	0.607	0.196	0.677
3	7	2800	0.393	0.577	0.184	0.682
1	7	3000	0.592	0.659	0.067	0.899
2	7	3000	0.357	0.437	0.080	0.817
3	7	3000	0.547	0.699	0.152	0.783
1	7	3200	0.402	0.501	0.099	0.803
2	7	3200	0.523	0.573	0.051	0.912
3	7	3200	0.306	0.762	0.457	0.401
1	7	3500	0.394	0.480	0.086	0.822
2	7	3500	0.496	0.691	0.195	0.717
3	7	3500	0.398	0.442	0.043	0.902
1	9	2200	0.464	0.543	0.079	0.854
2	9	2200	0.338	0.395	0.057	0.857
3	9	2200	0.469	0.429	-0.041	1.095
1	9	2500	0.412	0.452	0.040	0.911
2	9	2500	0.559	0.454	-0.104	1.230
3	9	2500	0.312	0.365	0.053	0.855
1	9	2800	0.470	0.623	0.153	0.755
Table 13 continued						

2	9	2800	0.428	0.531	0.103	0.806
3	9	2800	0.305	0.387	0.082	0.788
1	9	3000	0.305	0.454	0.149	0.672
2	9	3000	0.470	0.444	-0.027	1.060
3	9	3000	0.431	0.501	0.070	0.860

APPENDIX D

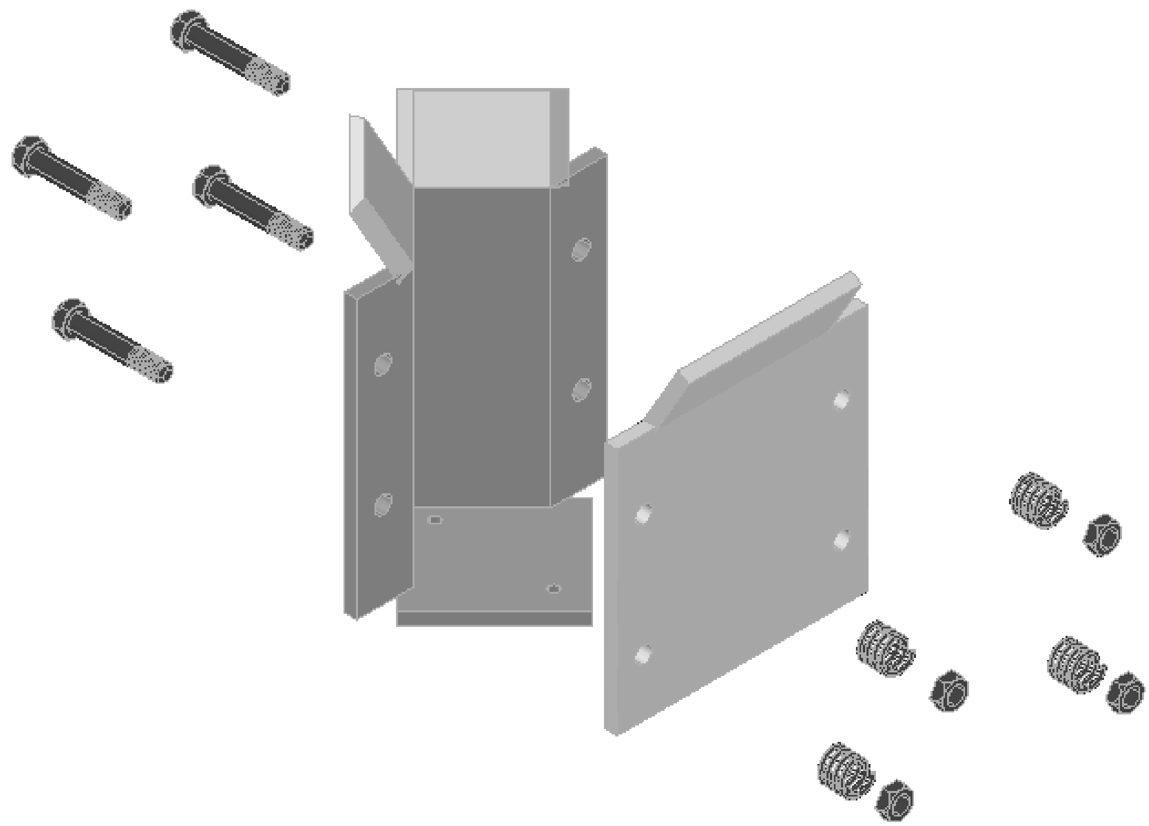


Figure D.1: Drawing of cup design

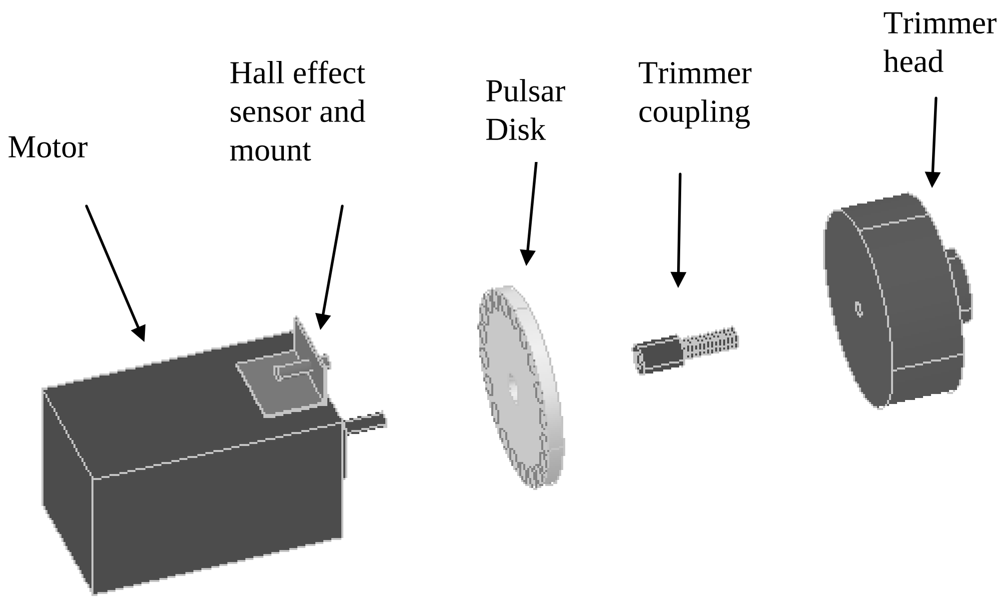


Figure D.2: Drawing of electric motor with sensor and pulsar disk and trimmer head

APPENDIX E

Table 14: Estimated cost of a production-model stripping machine.

Part	**Cost**	**Number**	**Total**
Trimmer Motors	$200.00	3	$600.00
Conveyor Motor	$285.00	1	$285.00
Conveyor Chain & Links	$115.00	1	$448.00
Structure	$170.00	1	$170.00
Gear Drive	$250.00	1	$250.00
Gears	$30.00	2	$60.00
Electric Parts	$50.00	1	$50.00
Cup Springs	$6.00	5	$30.00
Cam Followers	$17.00	24	$408.00
Cups	$15.00	24	$360.00
Initial Cam	$50.00	1	$50.00
Final Cam	$50.00	1	$50.00
Brushes	$6.00	6	$36.00
Trimmer Heads	$30.00	3	$90.00
Conveyor Materials and Parts	$200.00	1	$200.00
Nuts and Bolts	$750.00	1	$750.00
Pillow Bearings	$46.00	12	$552.00

Total Parts Cost			$4,389.00
Fabrication Cost			$4,389.00
Overhead Cost/Profit			$4,389.00
Projected Machine Price			$13,167.00

REFERENCES

Casada, J.H., J.N. Walker, and L.R. Walton. 1976. Removing burley tobacco leaves from the stalk, *Tobacco Science* XX: 69-70.

CTGR. 2009. Mechanical stripper/grader focus group summary. 2009. Center for Tobacco Grower Research. Knoxville, Tenn.: Available at: http://tobaccogrowerresearch.com/projects.html. Accessed 23 March 2010.

Duncan, G. A. 2006a. Gathering belt stripping conveyor [Online Video]. Ky. Coop. Ext. Service: University of Kentucky-BAE Dept.: Retrieved from http://www.bae.uky.edu/ext/Tobacco/Multimedia/HutchensGBeltStrM.wmv

Duncan, G. A. 2006b. Stripping with dual-chain stick conveyor on Wimpy Farm [Online Video]. Ky. Coop. Ext. Service: University of Kentucky BAE Dept.: Retrieved from http://www.bae.uky.edu/ext/tobacco/Multimedia/WimpyFmM.wmv

Duncan, G. A. 2006c. Unpublished table. Overview of significant labor reductions in burley production (1980-2006). Lexington, Ky: University of Kentucky BAE-Dept.

Duncan, G. A. 2007. Burley equipment and facilities overview. Ky. Coop. Ext. Service: University of Kentucky-BAE Dept.: Unpublished PowerPoint presentation

Duncan, G. A. and B. Tapp. 1984. Evaluation of burley stripping machines. Kentucky Biosystems and Agricultural Engineering pamphlet.

Duncan, G. A. and J. Wilhoit. 2007. Mechanical & hand stripping, UK Woodford Co. research farm: Initial trials with Carolina Tobacco Services2006 version tobacco stripping machine and UK prototype stalk chopper & pallets [Online Video]. Ky. Coop. Ext. Service: University of Kentucky-BAE Dept.: Retrieved from http://www.bae.uky.edu/ext/Tobacco/Multimedia/WdfrdStrp8M.wmv

Duncan, G. A., G. Palmer, and A. Bailey. 2008. Stripping and preparation of tobacco for market. In *2008 Kentucky Tobacco Production Guide*, 52-54. Lexington, Ky.: Ky. Coop. Ext. Service: University of Kentucky-College of Agriculture.

Eodiss Systems. 2010. Unpublished video (in French). Lexington, Ky.: University of Kentucky BAE dept.

Foreman, L. F. 2006. Tobacco production cost and returns in 2004. USDA Reference No. TBS-260-01. Washington, D.C.: GPO.

Gooch, P. Burley Mechanization: Balancing efficiency and quality. Tob. Rep.. December 1983.

Isaacs, S., and S. D. Mundy. 1988. Labor efficiency comparisons of the carousel and conventional systems for stripping and grading burley tobacco. *Tobacco Science* 32: 92-95.

Miyake, Y., and K. Manzawa. 1989a. Leaf stripping machine for stalk-cut tobacco. *Tobacco Science* 33: 1-4.

Miyake, Y., and K. Manzawa. 1989b. Tobacco leaf-stripping machine. U.S. Patent No. 4836220.

Morrison, J. E. Jr., and E. E. Yoder. 1972. Stalk-cut tobacco stripper development. *Transactions of the ASAE* 15 (2): 299-302 and 307.

Morrison, J. E. Jr., and E. E. Yoder. 1973. Cured tobacco leaf stripper. U.S. Patent No. 3765424.

Morrison, J. E. Jr., and E. E. Yoder. 1975a. Mechanical stripping characteristics for stalk-cut tobaccos. *Tobacco Science* XIX: 10-12.

Morrison, J. E. Jr., and E. E. Yoder. 1975b. Topping treatment effects on mechanical stripper performance in cured burley tobacco. *Tobacco Science* XIX: 136-138.

Patterson, C. D. 1983. Tobacco leaf-stripping machine. U.S. Patent No. 4407305.

Pinkham, J. R. 1981. Apparatus for stripping leaves from a stalk cured tobacco plant. U.S. Patent No. 4282888.

Range, A. P. 1984. Tobacco leaf grading and stripping apparatus. U.S. Patent No. 4429861.

Shirley, T. and Duncan, G. A. (Ed.). 2005. Single-chain stalk conveyor for stripping tobacco [Online Video]. Ky. Coop. Ext. Service: University of Kentucky-BAE Dept.: Retrieved from http://www.bae.uky.edu/ext/Tobacco/Multimedia/StrTbC1a.wmv

Wells, L. G., and M. J. Bader. 1990. Automated sorting of oriented tobacco leaves. *Applied Engineering in Agriculture* 6(1): 19-23.

Wilhoit, J. 2008. Unpublished data. Lexington, Ky.: University of Kentucky BAE dept.

VITA

Robert G. Sperry was born on May 12, 1985. He was raised in northern Boone, Kenton and Campbell Counties. He attended Covington Catholic High School and excelled in both science and art. In 2003, looking for a small liberal arts school away from home, Robert attended Transylvania University in Lexington, Ky. Here he was a member of Delta Sigma Phi fraternity and received a bachelor's degree in Physics. Upon graduating in May 2007, he decided to further his education at the University of Kentucky in the Biosystems and Agricultural Engineering Department. With only a degree in Physics, his first year was spent taking general level engineering courses and working for the department. He concluded his research in December 2010. During his graduate career he was inducted into the Alpha Epsilon Honorary Society for Agricultural Engineering.

Robert G. Sperry

Robert G. Sperry