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Development of an Automated Mechanical Intra-Row Weeder for Vegetable Crops

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Development of an automated mechanical intra-row weeder

for vegetable crops

by

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ABSTRACT

Weed management is one of the tedious operations in vegetable production. Because of labor costs, time and tedium, manual weeding is unfavorable. The introduction of chemical weed control methods has alleviated these undesirable factors. However, the emergence of herbicide-resistant weeds, environmental impact and increasing demand for chemical free foods has led to investigations of alternative methods of weed control. Most implements employing mechanical cultivation cannot perform weed control close to the crops, and existing intra-row weeders have limitations. A mechanical weeding actuation system was designed, and a prototype was constructed. This actuator was developed to mechanically control intra-row weed plants. The mechanical weeding actuator consisted of a belt drive system powered by an integrated servo motor and a rotating tine weeding mechanism powered by a brushless dc motor. One of the major challenges in this project was to properly design the actuator and its weeding mechanism for effective intra-row weed control. A prototype actuator was manufactured and a series of tests was conducted to determine actuator efficacy and the corresponding force and speed requirements of the actuator. The actuator would be combined with a machine vision system for detecting crop plant locations and guiding the weeding actuator to execute mechanical weeding operations without damaging crops.

In the first field experiment, the performance of the first version of the intra-row weeder was investigated across three factors: working depth, travel speed and tine mechanism rotational speed. There was evidence of differences in weed control efficacy across travel speeds. Using least square means, the slowest travel speed of 0.8 km/h had an average reduction in weed canopy area of 58.2% with standard error of 2.7% compared with the medium travel speed of 1.6 km/h with an average reduction in weed

canopy area of 52.6% with standard error of 2.7%. The fastest travel speed of 2.4 km/h had an average reduction in weed canopy area of 42.4% with standard error of 2.7%.There was no statistical evidence of differences in power consumption across working depth, travel speed, or rotational speed. With increasing working depths, reduction in weed canopy area and power consumption tended to increase.

With a revised version of the rotating tine weeding mechanism, a second field experiment was also conducted using three factors; tine shape, travel speed and rotational speeds. The results showed that there was no significant difference in reduction in weed canopy area across tine shapes. However, there was some indication that weed control efficacy decreased as travel speed increased. There was evidence of differences in power consumption across rotational speeds. The fastest rotation speed, 536 rpm, had a mean power consumption of 182 W and standard error of 9.4 W. The lowest rotation speed, 350 rpm, had the lowest mean power consumption of 123.5 W and a standard error of 9.4W.

CHAPTER 1. GENERAL INTRODUCTION

Introduction

Vegetable crop production is a major contributor to the US economy with a value of 11.2 billion dollars in 2010, an increase of three percent compared to 2009. The total area harvested was 1.78 million acres, with California having the largest acreage of 751,500 acres. The vegetable crops with the largest production were onions and lettuce, with a total of 3.3 million metric tons (USDA & NASS, 2011).

To achieve a high yielding vegetable production, good agricultural practices are required. One of the most important practices is to properly manage weeds. Weeds affect crop yield due to competition to acquire plant nutrients and resources (Slaughter et al.,2008;Weide et al., 2008). Weeds have very fast growth rates compared to crops, and if not treated and managed, they may dominate the field.

There are various methods for controlling weed infestation in crop production. Some farmers adopt agronomic practices that improve crop competitiveness such as planting vigorous crop seeds at relatively shallow depths and planting right after a weed-control operation. This method is used to prevent the weed seeds from germinating before the crop is planted and to ensure that crop plants emerge before the weed plants. This practice will not only ensure a maximized crop yield and reduce weed infestation, but also minimize any economic losses (Maxwell and O’Donovan, 2007). The above practice should be applied for controlling weeds if the canopy closes and does not allow much light onto the ground surface where weeds will germinate and grow. However, weed control is still required during the crop production cycle.

Another weed control method that is practiced is to increase the crop density in the field. By filling the field with crops, weed seed germination rates are reduced (Blackshaw et al., 2007). However, the distance between plants are reduced and might affect other field operations such as fertilizer spraying or harvesting.

Weed management is a strategy that make a desired plant population successful in a particular agro ecosystem using knowledge of the ecology of the undesired plants, that is the weeds (Ghersa et al., 2000). The most effective method of weed management is by making physical contact with the weeds themselves, which is weed control. Currently, there are several ways of controlling weeds, either by using manual, chemical, mechanical or biological means.

The earliest and the simplest weed control method is manual weed control. This method was and is accomplished by a person bending down and using their hands to pull weeds out of the soil. This method then advanced to hand tools, from using a stick to using a hand-hoe. The labor required for weeding is expensive, time consuming and difficult to organize (Weide et al., 2008). Gianessi and Reigner (2007) reported that manual labor costs have increased from $0.10/hour in 1940s to $1.00/hour in 1960s. As of 2005, the rate had further increased to $10/hour. Furthermore, problems such as back pain due to frequent repetitive bending caused manual weed control to be avoided. In areas such as California, hoe weeding and hand weeding was banned due to permanent back damage in workers.

Before the existence of chemical weed control, mechanical weed control was the best option to solve issues related to manual weeding. In mechanized agriculture, there were times where weeding tools were pulled by draft animals such as buffaloes and horses, which now in the developed world have generally been replaced by tractors. There are various types of mechanical weeding implements in the market that use three main techniques: burying weeds, cutting weeds and uprooting weeds. The burial of weeds through the action of tillage tools, and is usually done during land preparation. For cutting and uprooting weeds, there are two types of machinery available: inter-row weeders and intra-row weeders. Inter-row weeding is a weeding method that accomplishes between-planting row weeding, while intra-row does within-planting-row weeding. Mechanical inter-row weeders such as inter-row cultivators, rotary cultivators and basket weeders are available in the market (Cloutier et al., 2007). Inter-row cultivators and rotary cultivators are agriculture implements that consists of suspended cutting blades that perform weed control action. The basket weeder is an implement consisting several rolling rectangular-shaped wires, forming a round basket. The efficacy of the weeding operation often depends on factors such as plant height, rooting depth and forward speed. More aggressive operations, generally result in higher weed control efficacy, but often increase the risk of damaging crop plants.

There are also a wide range of mechanical intra-row weeders available. Cloutier et al. (2007) and Weide et al. (2008) reported the usage of finger weeders and torsion weeders. A finger weeder is a simple mechanical intra-row weeder that uses two sets of truncated steel cone wheels with rubber spikes, or ‘fingers’ that point horizontally outwards. Torsion weeders use flexible spring tines connected to a rigid frame and bent so that two short segments work close together and parallel to the work surface. They concluded that these machines will work effectively when precise and accurate steering is used. This was the reason why these weed attachments were integrated with precision cultivators. Furthermore, these machines can only perform weed control when the crops are well-rooted, because if the intra-row weeders mentioned above have contact with the crops, the crops will not be damaged. This requirement causes a difficulty in controlling weeds at very early planting stage.

One of the most promising technologies for intra-row weeding is the brush weeder. Cloutier et al. (2007) reported that the brushes of the brush weeders are made of fiberglass and are flexible. These brushes can be vertically-rotated or horizontally rotated. These weeders mainly uproot, but also bury and break weeds. A protective shield or cover can be installed to cover the crop from damage. An operator can also be added to steer the brushes to cultivate as close as possible to the crop but without damaging the crops.

In modern agricultural systems, chemical-based weed control is widely used. The implementation of conservation tillage practices to promote soil quality, to minimize soil erosion, or to simplify crop management has increased reliance on herbicides (Weaver et al., 2007). The appearance of herbicides in the mid-20th century contributed to a decreased reliance on mechanical weeders (Cloutier et al., 2007). Gianessi and Reigner (2007) reported that during those years, labor became scarce and more expensive especially after World War II.

Currently, however, it is becoming increasingly difficult to ignore the usage of herbicides in weed management because of its effectiveness to accomplish weed control and at the same time reduce yield loss. However, renewed interests in mechanical weeding have grown due to environmental concerns, the growing demand for pesticide-free produce and also the growth of herbicide-resistant weeds (Upadhyaya & Blackshaw, 2007).

Biological weed control is a weed control method using specialized herbivorous natural enemies of problematic plants in agricultural or natural environments (Blossey, 2007). Héraux et al. (2005) used allelochemical-releasing organisms to control weeds in transplanted vegetable fields. Hakansson (2003) also reported several well-known examples of biological control of weeds, such as the control of an Australian weed, prickly pear cactus using a moth that originated in South America. The biological approach has its success and failures, and some inconsistencies make this method not widely practiced.

Advances in computers and sensors have contributed in the use of automation for agriculture machinery generally, and for weeding machines specifically. With automation, the weeding is operated electronically which reduces human intervention and optimizes the power provided by the machine. Automated machines also offer the possibility to determine and differentiate crop from weeds, and at the same time, remove the weeds with a precisely controlled device (Bakker, 2009). Several researchers have attempted to use automation for intra-row weed control. Tillett et al. (2008) tested an automated weeding machine using computer vision to detect plants and a rotating half-circle disc for the weed control. Astrand and Baerveldt (2002) developed an agricultural mobile robot using a perpendicular rotating weeding tool for weed control and two cameras – one near-infrared filter camera to locate crop row position and another color camera to identify crop plants. Cloutier et al. (2007) reported on the “Sarl Radis” hoe developed in France. This automated weeder used light interception for crop detection, and a control system that controlled the lateral motion of a hoe relative to the crop row and around the crop plants.

Griepentrog et al. (2006) developed an autonomous intra-row weeder based on RTK (Real-time Kinematics) GPS. This rotor weeder was controlled with an electro-hydraulic motor system to power eight rotating tines that could be controlled individually to follow two different tine trajectories. This machine has the same concept as the brush weeder, using rotating tines or brushes to perform weed control.

Automation should be the next step ahead for the rotating tine concept since it has produced very good weed control efficacy. In addition, automation can help reduce issues such as labor, human intervention and time consumption associated with manual weed control. Current automated weeding machines have not employed electrical power for the rotating tine weeding mechanism. Electronic control could provide more precise and reliable response with low maintenance.

The research documented in this thesis investigated intra-row weeding using a rotating tine weeding mechanism that was powered electrically. Different parameters that could affect weed control efficacy were studied. This research will be useful for researchers that would like to further investigate automated intra-row weed control. Vegetable growers can use the information in this thesis to identify the correct settings for intra-row weed control, specifically when using rotating tines mechanisms for weed removal. Agricultural machine manufacturers can also benefit from the research to produce better intra-row weeders.

Objectives

The overall goal of this research was to investigate the design and performance of a rotating tine mechanism intended for automated intra-row mechanical weeding in vegetable crop production. The specific objectives of this research were to:

a) Study weed control efficacy using different machine settings such as working depth, travel speed, rotational speed and number of tines.

b) Study the power consumption of the system with respect to different machine settings.

Thesis Overview

This thesis contains five chapters. In Chapter 1, the general introduction of the research is presented. In Chapter 2, the background of the research area is described. In Chapter 3, the design work of the prototype is presented. Chapter 4 contains a paper entitled *Performance and Evaluation of a Rotating Tine Weeding Mechanism for Automated Intra-row Weeding for Organics Vegetable Production*. Chapter 5 contains general conclusions and recommendations for future work.

CHAPTER 2. BACKGROUND

Vegetable crop production is a major contributor to the US economy with a value of 11.2 billion dollars in 2010, an increase of three percent compared to 2009. The total area harvested was 1.78 million acres, with California having the largest acreage of 751,500 acres. The vegetable crops with the largest production were onions and lettuce, with a total of 3.3 million metric tons harvested annually (USDA-NASS, 2011). Increases in vegetable production are mainly due to the increase of consumer demand in obtaining nutritious and healthy foods. Government programs such as the National Fruit and Vegetable Program, that encourages people to eat a daily diet consisting of 4 to 6-1/2 cups of fruits and vegetables a day to promote good health and reduce the risk of health problems, may have also contributed to this increase (Stewart and Lucier, 2009; CDC, 2011).

In vegetables crop production, weed management is very critical and is considered one of the most important operations. Weeds are known to be very competitive in obtaining moisture, sunlight and nutrients. This competitive nature will unfortunately affect the crop yield (Slaughter et al., 2008). Gianessi & Sankula (2003) reported that most crops require that the field be kept weed-free during the first four to six weeks after planting to prevent serious yield losses from early season weed competition.

Throughout this chapter, methods of weed control are assessed by their efficacy, usually in percentages of reduction in number of weed plants or weed canopy area before the weed control operation to after. Depending on the research, the percentages can represented the reduction in the number of weed plants before and after the weed control operation or the reduction in canopy area before and after the weed control operation. Vanhala et al. (2004) prepared guidelines for physical weed control research and reported two methods of assessing weed control efficacy: quantitative methods and qualitative methods. Quantitative methods such as weed counts, weed biomass and weed seed production are used depending on the weed species available in the plot. These types of measures are ideal because they show actual measured values of weed density or biomass at a certain point in time. Qualitative method such as visual estimation of weed control is usually done when quantitative methods are too time consuming and become too costly. It is a quicker and easier method to conduct, but also difficult to rate and analyze. The choice of using either qualitative or quantitative measurements highly depends on the time and resources needed to make the assessments.

There are several methods that can be used for weed control. Manual weed control is a method using bare hands or handheld tools to uproot weeds, while mechanical weed control involve the use of machines to perform weed control. Chemical weeding uses herbicides to control weeds, and biological weed control applies other organisms for weed control.

Manual Weed Control

The earliest and the simplest of all technologies was manual weed control. Manual weed control started with farmers using their hands to uproot the weeds. The technology then advanced to hand tools, from using a stick to using a hand-hoe (Cloutier et al., 2007). Manual weeding using human hands, provides a very effective weed control, but requires substantial human effort and energy (Table 2.1). From the study by Gianessi and Reigner (2007), asparagus required the lowest time for hand weeding, 12 hours per hectare, and onions required the highest time for hand weeding operation, 158 hours per hectare. A cause for this low weeding rate for onions compared to other crops like asparagus was that onions have a smaller crop canopy, which allows more sunlight to penetrate onto the soil, thus creating a higher probability for emergence weeds. The data in this table was estimated from a series of studies conducted in the 1990s by USDA, Weed Science Society of America (WSSA) and American Farm Bureau Federation (AFBF). Slaughter et al. (2008) indicated that hand weeding eliminated only 65 – 85% of the weeds for cotton production, mainly due to workers mistaking weeds for crop plants or missing weeds. It was also reported that manual weeding using long-handled hoes would damage the crops while also missing some of the weeds (Gianessi and Reigner, 2007). Hoeing is also time consuming and can lead to back injuries to workers.

Earlier in California, manual hoes were used primarily for weeding most vegetable crops. Farm workers complained of suffering permanent back injury due to extended periods of hoe weeding. As a result, in 1975, hoe weeding was banned by the California Industrial Safety Board. The ban was then extended to hand weeding in 2004, by the California Occupational Safety and Health Standards Board because of concerns for farm laborer health. Nevertheless, organic crop growers were exempted from this ban because hand weeding is one of few weed control options available to them in the context of their chemical-free practices. Walz (2004) conducted a National Organic Farmers' Survey and concluded that organic farmers cited weeds as one of the major causes of reduced profit after weather-related losses, high input costs and high labor costs, in that order. Earthbound Farms, the largest organic producer in North America, mentioned that weed control was a time consuming and very costly part of their operations since they depended on mechanical cultivation and hand weeding. Their farmers had to spend up to $1000 per acre to control weeds (EFO, 2011).

Table 2.1: Hand weeding work rates for different types of crops (Modified from Gianessi and Reigner, 2007).

Crop	Hand weeding (h/ha)
Asparagus	12
Broccoli	50
Carrot	35
Celery	149
Corn	12
Cucumber	74
Dry bean	40
Green bean	30
Green pea	30
Hot pepper	149
Lettuce	94
Mint	45
Onion	158
Peanut	15
Spinach	50
Sweet potato	59
Tomato	92

Mechanical Weeding

As agriculture became more mechanized, weeding tools were developed that were pulled by draft animals such as buffaloes and horses. As time progressed, these implements evolved and were adapted to tractors as the source of draft. There are many types of mechanical weeders in the market that can use three main physical techniques for controlling weed: (1) burying weeds, (2) cutting weeds and (3) uprooting weeds. Burial of weeds is accomplished through the action of tillage tools (Gianessi and Sankula, 2003) and is usually done during land preparation when soil conditions are enhanced through tillage. The goals of tillage include reducing the soil strength, covering plant residue, rearranging aggregates and also removing weeds. Cutting and uprooting weeds are performed by mechanical tearing and breaking the weeds from the soil, and is usually done by mechanical cultivation after the crop is planted and has emerged. The majority of the manufacturers who sell mechanical weeders, produce weeders that are designed to control weeds between rows, or in the inter-row region (Cloutier et al., 2007). There are only a few machines that are designed to do within crop row weeding, or intra-row weeding.

Mechanical Inter-row Weeding

This type of weed control is generally widespread and used by farmers who do not use herbicides. The objective of inter-row cultivation is to cultivate as much of the inter-row area as possible without damaging the crop. Cultivation can destroy weeds by completely or partially burying weeds, uprooting and breaking the weed root contact with the soil. However, there are limitations using this method. Weed control can only be done during the early crop stages because limited tractor and cultivator ground clearance and machine-plant contact may potentially damage the crop foliage at later growth stages (Cloutier et al., 2007). However, in spite of these limitations, there is a wide selection of cultivation implements that can be used for mechanical inter-row weeding.

Inter-row cultivators are the most common machine used for mechanical weed control. This agriculture implement consists of cultivating tools mounted on a toolbar that either rotate or sweep to move soil, bury, cut or uproot the weeds (Fig. 2.1). The sweeping type cultivators use triangular-shaped or duckfoot-shaped blades that are swept under the soil but near the soil surface. The blades vary in width, from as small as 5.1 cm (2 in.) to as large as 71.1 cm (28 in.). This type of cultivator does not require any PTO power. Recommended travel speeds for sweep type cultivators are 6.4 km/h to 11.3 km/h. Another type of cultivators are rotating type cultivators such as rotary tilling cultivators and rotary tillers, which are commonly used for inter-row weed control. However, the latter machine is more expensive, since it has been designed for multiple functions including other tillage applications such as strip-planting into cover crops and preparing permanent plant beds. These rotary tilling implements use individually suspended inter-row gangs or blades, which are mounted on circular discs with parallel linkages. The cutting blades or knives vary in width, from 12.7 cm to 152.4 cm (5 in to 60 in), and in configuration. Metal housings can be used to cover the tilling blades to prevent crop damage. Recommended forwards speeds for rotating type cultivators are 4 km/h (2.5 mile/h) to 8 km/h (5 mile/h) (Bowman, 1997).

Figure 2.1: Inter-row rotary cultivator for inter-row weed control (Tornado, 2011).

The basket weeder is an implement that consists of rolling rectangular-shaped quarter inch spring wire forming a round basket (Fig. 2.2). This basket weeder is ground driven, which means it does not require any power other than that provided through the draft force from the tractor. The basket weeder will remove weeds at the top surface of the soil, without moving soil into the crop row. This machine is suitable in moist soils in minimal clay content. It performs well at forward speeds of 6.4 km/h (4 mile/h) to 12.9 km/h (8 mile/h) (Bowman, 1997).

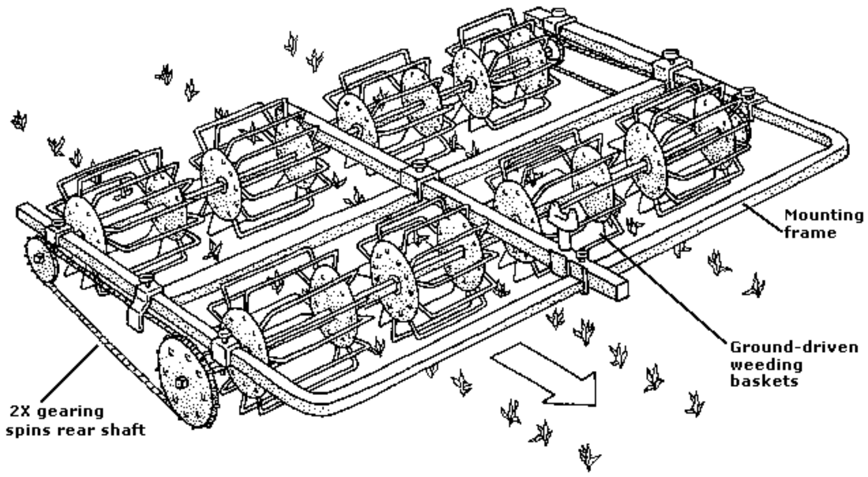


Figure 2.2: Basket weeder for inter-row weed control (Bowman, 1997).

Mechanical Intra-row Weeding

Mechanical intra-row weeders control weeds within the crop rows. These weeders accomplish their goal using two different approaches depending on the crop density. The first approach is to use selective machines or add-on tools that can perform weed control close to the crop, without damaging the crop itself. This approach does not require the any sideways movement of the weeder. The second approach is to use machines that have weeding tools that move sideways to conduct weed control around the crop canopy. Below are some of the machines that have been reported to be effective in weed control.

Finger Weeder

The finger weeder is a simple mechanical intra-row weeder that uses two sets of steel cone wheels to which rubber spikes, or ‘fingers’ are affixed. These fingers point horizontally outwards at a certain angle. These finger weeders operate from the side and beneath the crop row with ground driven rotary motion (Fig. 2.3). The rubber fingers penetrate the soil, and just below the soil surface, remove small weeds that are near the fingers. The finger mechanism performs best in loose soil, but performs poorly in heavily crusted or compacted soils or in situations where long stemmed residue is present. This type of weeder is effective against young weed seedlings up to 25.4 mm (1 in.) tall and interacts gently with well-rooted crops. The recommended operating depth is 12.7 mm (0.5 in.) to 19.1 mm (0.75 in.). The recommended forward speed to use with this weeder is 4.8 km /h to 9.7 km/h (3 to 6 mile/h). Alexandrou (2004) evaluated the finger weeder and obtained weed efficacy results of 61% of the intra-row weeds killed in organic corn. A disadvantage of using this method, however, is that the tractor must be steered very accurately so that the finger mechanism can work as close as possible to the crop rows (Bowman, 1997; Cloutier et al., 2007;Weide et al., 2008).

Figure 2.3: Finger weeder uses rubber spikes that are pointed at an angle towards the crop (Weide et al., 2008).

Torsion Weeder

The torsion weeder is another machine available for intra-row weed control. Torsion weeders use spring tines connected to a rigid frame and that are bent so that two short tine segments are parallel to the soil surface and meet near the crop plant row. This arrangement allows crop plants to pass through the tine pairs (Fig.2.4). The coiled spring tines allow the tips to flex with soil contours and around established crops. These weeders have been tested in Europe and North America for horticultural crops with very good results. The weeder also reduced the weed density to 60-80% of the original weed population. However, it also requires very accurate steering with relatively low forward velocities, and hence has a low working capacity. Torsion weeders are often used together with precision cultivators to perform efficacious weeding (Bowman, 1997; Cloutier et al., 2007;Weide et al., 2008).

Figure 2.4: Torsion weeder uses flexible coil spring tines to sweep the weeds (Weide et al., 2008).

Brush Weeders

Brush weeders uses flexible brushes made of fiberglass or nylon rotated about vertical or horizontal axes. These weeders mainly uproot, but also bury and break weeds. A protective shield or cover can be installed to cover the crop from damage. An operator is required to steer the brushes to cultivate as close and as many weeds as possible without damaging the crop plants (Fig. 2.5; Cloutier et al., 2007).

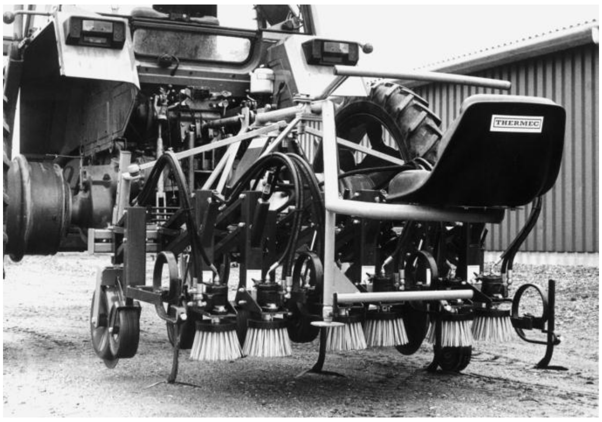


Figure 2.5: Vertical-rotating brush weeder use hydraulics and require an operator to control the brushes (Melander, 1997).

Fogelberg and Gustavsson (1999) investigated the use of a brush weeder for intra-row weed control in carrots, and reported that the brush weeder are effective at early weed growth stages, specifically in the 2-4 true leaf stages. Forty-five to ninety percent of the weeds were uprooted using a working depth of 15 mm. They concluded that the major mechanism of weed control obtained by brush weeding was uprooting, because brush weeding applies a greater uprooting force compared to the root anchorage force for the weed plants.

Kouwenhoven (1997) also reported on research investigating a brush weeder for intra-row weed control. In an experiment conducted in maize and sugar beet crops, it was determined that the best rotational speed for the brush weeders was 240-360 rpm with a forward travel speed of 2 km/h. Results showed that brush weeding for maize was more effective than manual weeding. However, sugar beet plant damage was reported due to steering inaccuracy and fine soil created by the brushing effect, combined together with the moist weather conditions, resulted in additional weed plant emergence after the weeding operation.

ECO-Weeder

The ECO-weeder is an intra-row mechanical weeder that is three-point hitch mounted and trails behind a tractor. It uses the tractor's power take-off (PTO) to drive a belt system that powers two discs with tines (Fig. 2.6). This machine is quite similar to the brush weeder described above, but uses a mechanical drive and does not require any hydraulic power. It is a good option for small production-scale vegetable growers because of its low price and low maintenance costs. From interactions with local farmers, it was reported that the minimum tractor size needed to power the ECO-weeder is 14.7 kW (20 hp), and the PTO speed required is 540 rpm. It still requires an operator to move two rotating discs with vertically oriented tines in and out of the crop row. The forward speeds used by farmers are usually 0.8 km/h (0.5 mph) to 2.4 km/h (1.5 mph), and the rotation speed of the weeding element was estimated to be 150 to 300 rpm, similar to that of the brush weeder as reported by Kouwenhoven (1997). It was reported by the manufacturer that the ECO-weeder can save up to 60% of weeding costs when compared to manual weeding due to the reduced labor requirements: two workers instead of 8 workers(Univerco, 2011).

Figure 2.6: ECO weeder uses rotating weeding mechanisms with tines (Hillside Cultivator Company, 2011).

Chemical Weed Control

In the mid-20th century, the use of mechanical weeders decreased as herbicide spraying was introduced in North America and Europe (Cloutier et al., 2007; Hakansson, 2003). The usage of herbicides became more favorable because labor became limited and more expensive. After World War II in the U.S., labor costs increased and labor workers became scarce, as workers were more eager to work in the cities rather than staying in the rural areas. As a result, labor rates increased from $0.10/hour in 1940s to $0.50/hour in 1950s and $1.00/hour in 1960s. In addition, the cost of herbicide application was more economical and helped to reduce yield loss compared to standard practices such as mechanical cultivation or manual weeding (Gianessi and Reigner, 2007). Gianessi and Reigner (2006) reported that the herbicide cost for vegetable crops increased slightly from 2001 to 2005. They also reported that manual weeding costs also increased, with hand weeding costs increasing from $8.75/hour in 2001 to $10/hour in 2005. Mechanical cultivation costs also increased from $4.50/acre to $5.84/acre. Herbicide application cost was slightly lower, estimated at $4.00/acre in 2001 and increased slightly to $5.21/acre in

2005, based on an 18.3 m (60 ft.) self-propelled boom sprayer. These costs provide one reason why vegetable farmers tend to use chemical weeding, because of the cost advantage over manual weeding.

Chemical weeding not only protects the crop from weed competition, but it also helps to reduce crop yield loss compared to mechanical cultivation. Mechanical cultivation has always had difficulties in performing cultivations in a timely manner, due to issues such as wet fields hindering tractor and equipment entry, leading to weed competition for crop plant nutrients (Hakansson, 2003). Gianessi and Reigner (2007) presented historical data indicating increases in yield due to chemical weeding. Researchers have also shown statistically that herbicides contribute to improved corn and soybean yield.

However, renewed interests in chemical weed control alternatives have grown due to environmental concerns, the growing consumer demand for pesticide-free produce and also growing herbicide resistance in weeds (Upadhyaya and Blackshaw, 2007). Herbicide application is also becoming more constrained with increasing pesticide use regulations, consumer concerns and a growing interest in organic foods (Slaughter et al., 2008).

Biological Weed Control

Biological weed control is a weed control method using specialized natural herbivorous enemies of problematic plants in agricultural or natural environments (Blossey, 2007). Heraux et.al., (2005) used allelochemical-releasing organisms, which are organisms that release a chemical substance that can suppress or stimulate other organisms, to control weeds in transplanted vegetable fields. Hakansson (2003) also reported several well-known examples of biological control of weeds, such as the control of an Australian weed, prickly pear cactus, using a moth that originated from South

America. This biological approach for weed control has its successes and failures, and some inconsistencies that make it difficult to adopt in practice.

Other Forms of Weed Control

There are also other types of non-chemical weed control methods such as flame weeding, pneumatic weeding, and laser weeding. These methods require other sources of energy to control weeds. The flame weeder, for example, requires propane gas to produce heat which elevates the temperature of the weed plants and either burns the weed biomass or causes weed plant cells to rupture and damage the plant structure (Fig.2.7). Pneumatic weeders require an air compressor, which injects compressed air into the soil to loosen and uproot small weeds (Fig.2.7;Bond et al., 2003). Both of these methods have substantial energy requirements. The flame weeder requires 28.2 to 131 liters of fuel per hectare (3 to 14 gallons of fuel per acre), depending on the intensity and coverage. The pneumatic weeder uses substantial power, requiring a 60kW tractor to produce high air pressure to control weeds in well-anchored crops. This is twice the power required for conventional hoeing (Weide et al., 2008). However, they are both suitable for organic production systems because their chemical-free approach with minimal soil disturbance.

Figure 2.7: A crop-row flame weeder using LPG gas to control weeds inside the crop row (Physical Weeding, 2011).

Figure 2.8: Pneumatic weeder uses air to blow out weeds (Weide et al., 2008).

Comparison Between Different Weed Control Methods

Various types of intra-row weed control method can be used, resulting in different costs. The various mechanical weed control methods were compared with chemical weed control and conventional manual weeding (Table 2.2) based on Edwards (2009) and Gianessi and Reigner (2007). Edwards (2009) provided a report for estimating farm machinery costs. Manual weeding has the highest cost, with $312/acre, while the lowest cost is chemical weeding. These costs were determined based on an hourly labor cost of $12. Because of this big difference in cost alone, farmers tend to use chemical methods for weed control. In addition, the weed control efficacy of chemical weeding can be almost 90%. The lowest cost mechanical method that can be used is the torsion weeder, which costs $22/acre and produces a weed control efficacy of almost 80%. The work rate of manual weeding was based on lettuce manual weeding (Gianessi and Reigner, 2007). The chemical weeding work rate was based on a 6.1 m (20 ft.) boom sprayer operating at a speed of 9.7 km/h (6 mile/h). The finger weeder work rate was based on an estimated operating width of 0.76 m (30 in.), the torsion weeder work rate was based on an estimated operating width of 0.18 m (7 in.) of a single-row torsion weeder, the brush and ECO weeder work rates were based on an estimated operating width of 0.64 m (25 in.) of a twin weeding mechanism, single-row brush weeder and ECO weeder. The flame weeder work rate was based on an estimated operating width of 0.76 m (30 in.) of a tractor mounted flame weeder.

Table 2.2: Comparison of different intra-row weeding machines with chemical, flame and manual weeding in terms of cost, operating speed, operating depth and weed control efficacy.

Method	Cost (USD/acre)	Work rate (ha/hr)	Operating Speed (km/hr)	Operating depth (mm)	Weed control (%)
Chemical weeding	15	2.9-5.9	4.8-9.6	On surface	80-90
Torsion weeder	22	0.1-1.4	6.4-8.1	0-25	60-80
Finger weeder	38	0.3-0.6	4.8-9.6	10-40	55-60
ECO weeder	44	0.05-0.15	0.8-2.4	25-50	60-80
Brush weeder	74	0.1-0.3	1.6-4.8	25-50	60-80
Flame weeder	70-90	0.1-0.5	1.6-6.4	On surface	80-90
Manual weeding	312	0.01	NA	0-50	65-85

Automated Technology in Weeding

Automation is defined as the technique, method, or system of operating and controlling a process or mechanical device without human intervention and continuous input from an operator. Automation also optimizes the power provided by the machine, and thus often represents the substitution of energy input into a process with electronic hardware, sensors, actuators and software (Chancellor, 1981). Weed control, particularly within the crop row is a process that benefits greatly from the intelligence represented in manual weeding, but also from the higher work rates associated with mechanical weeding. Automation technology also been applied to weed control to combine the advantages of manual and mechanical approaches. By using automation, a machine offers the possibility to determine and differentiate the crop plants from weed plants, and at the same time, remove the weed plants with a precisely controlled device (Bakker, 2009). Slaughter et al. (2008) in a review on autonomous robotic weed control systems identified four core technologies needed for automated weed control: (a) guidance, (b) detection and identification, (c) precision in-row weed control and (d) mapping. He also described several intra-row weed removal mechanisms for robotic actuation. One of the mechanical-based designs was using mechanical knives that can rapidly position in and out of the crop row.

Row guidance systems can use machine vision for crop row detection and/or global positioning systems (GPS). Machine vision has the ability to identify crop rows at travel speeds ranging from 2.5 km/h to 10 km/h and produces very small errors ranging from 12 to 27 mm. Meanwhile, GPS has the ability to provide a lateral positioning accuracy along the row with RMS error of 6 cm, and the maximum error distance of 13 cm (Slaughter et al., 2008). However, row guidance systems requires that the crop be planted using Real Time Kinematics (RTK) GPS guided planting system or the crop rows mapped using some type of geo-referenced mapping technique.

Detection and identification of weeds and crop, is a very challenging task to conduct in real time. Weed identification techniques rely on machine vision systems and image processing techniques described by Gonzales et al. (2004) such as biological morphology, spectral characteristics and visual structure. Steward and Tian (1999) used environmentally adaptive segmentation algorithm (EASA) to develop real-time machine vision weed detection for outdoor lighting conditions. Tang et al. (2000) used color image segmentation using a binary-coded genetic algorithm (GA) for outdoor field weed identification under different lighting conditions.

Precision intra-row weed control can use mechanical, chemical, thermal or electrical approaches. Mechanically automated weed control such as the automated thinners use mechanical knives that travel in and out of the crop row or use a rotating hoe that could be height adjusted (Astrand and Baerveldt, 2002). Automated chemical weed control such as precision spraying system was developed using independent spray ports for spraying weeds in a spray map generated by vision systems (Lee et al., 1999). Electrical weed control was developed by applying high voltage (15-60kV) electrical discharge or continuous current to small weeds using precise probe position control (Diprose and Benson, 1984; Blasco et al., 2002). Precision thermal weed control involves the usage of infrared sensors to detect weeds and automatically opens the flame nozzle to burn the detected weeds (Merfield, 2011).

Examples of Automated Weeders

Tillett et al. (2008) tested a weeding machine using computer vision to detect plants. This automated intra-row weeder used a rotating half circle disc that rotated to avoid contacting the crop plants during weeding. A camera was mounted centrally on the implement at a height of 1.7 m looking ahead and down such that the bottom of the field of view was vertically below the camera and the full-width of the bed was visible over a length of approximately 2.5 m. The position of the plants along the crop row and their location relative to the rotating disc were detected using computer vision (Fig. 2.9). An experiment on a cabbage plot was conducted using an intra-row crop plant spacing of 0.3 m and a forward velocity of 1.8 km/h (0.5 m/s). Weeding treatments were conducted at 16, 23, and 33 days after transplanting (DAP). The best results were obtained at 16 and 23 days after planting, with 77% and 87% reduction in the number of weed plants, respectively. However, after 2 weeks of subsequent weed re-growth and new germination, the number of weed plants after the 16 DAP weeding treatment was still reduced by 74%, while number of weed plants after the 23 DAP treatment were still reduced by 66%. Under the experimental conditions, it was shown that performing weed control at an early stage succeeded in controlling later weed re-growth and new germination. This machine was commercialized under the name Robocrop (Inman, 2011).

Figure 2.9: Automated weeder machine using hydraulics to rotate semi-circle discs that are used for weed control (Tillett et al., 2008).

Astrand and Baerveldt (2002) developed an agricultural mobile robot with vision-based perception for weed detection and subsequent control. This machine required two cameras, one gray-scale camera with a near-infrared filter to obtain high-contrast images located at the front to identify the crop row location and direction, and a color camera to identify crop plants, located at the center of the machine, facing downwards towards the soil (Fig. 2.10). A weeding tool, which was a rotating wheel oriented perpendicular to the crop row, was located at the rear of the machine. The tool was lowered using a pneumatic cylinder when gap between crop plants was detected and provided some tilling action in the inter-crop plant area. At a speed of 0.2 m/s, the weeding robot showed good perception performance. The crop row detection camera was able to recognize crop rows based on a row-recognition algorithm with a ±2 cm error. The crop detection color camera successfully detected crops with using image segmentation techniques to classify weeds and crops using color and shape features. However, the weed control efficacy of the machine was not reported. The research focused more on the perception system for crop row detection and crop detection, and not on weed control in particular.

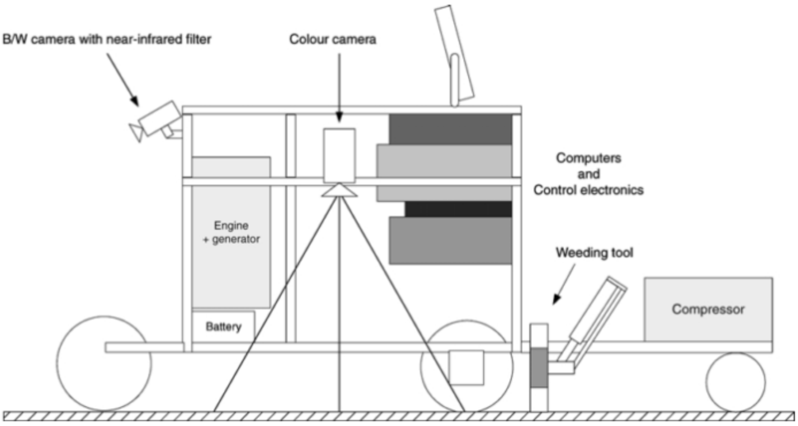


Figure 2.10: Major components of the mobile robot (Astrand and Baerveldt, 2002).

Cloutier et al. (2007) reported on the in-row hoe weeder developed by a France firm, Sarl Radis (Fig. 2.11). This automated weeder sensed reflected light from the field surface to detect crop plants, and used a control system to control the motion of a hoe around the crop plants. It was originally developed for transplanted crops, and can only be operated when the weeds are substantially smaller than the crop plants. This is usually the condition with conventional weeding, in which weeds are controlled while they are still small compared to the crop plants. The working speed of the prototype was reported to be 3 km/hr. Farmers Guardian (2007) reported that the Dutch Applied Plant Research organization is continuing to develop this prototype, hoping to achieve an operating speed of 4-6 km/h and to effectively control higher population weeds between the crops.

Figure 2.11:Sarl Radis intelligent weeder from France uses an automated hoe that moves in and out of the crop row (Cloutier et al., 2007).

Griepentrog et al. (2006) developed an autonomous intra-row weeder based on RTK (Real-time Kinematics) GPS to locate the weeder relative to crop seed maps that were developed at the time of crop seeding. This weeder used a rotary weeding mechanism that is rotated using an electro-hydraulic motor. The mechanism consisted of eight tines with tine tips having an outer diameter of 0.234 m (Fig. 2.12). These tines can be controlled individually to follow two different tine trajectories. The non-activated tine trajectories can be described as a cycloid curves, where a curve traced by a point on the circumference of a circle as the circle rolls on a straight line. The other trajectory is where the tine moves in and out of a crop row. The research claimed that the rotor weeding mechanism has the ability to control weeds inside the crop row and till the soil as close as possible to the crop plants without damaging them. The weeding effect of these tines is accomplished through uprooting, weed soil coverage and root cutting. The parameters to achieve a particular tillage effect are the ratio of forward speed to rotational speed, the diameter of tine rotation, the number of tines, the shape and design of tine tips and the lateral offset to crop rows. The machine was attached to an autonomous tractor driven using RTK GPS and the lateral shift of the weed mechanism and the activation of the rotor tines was based on seed maps from the previous sowing operations.

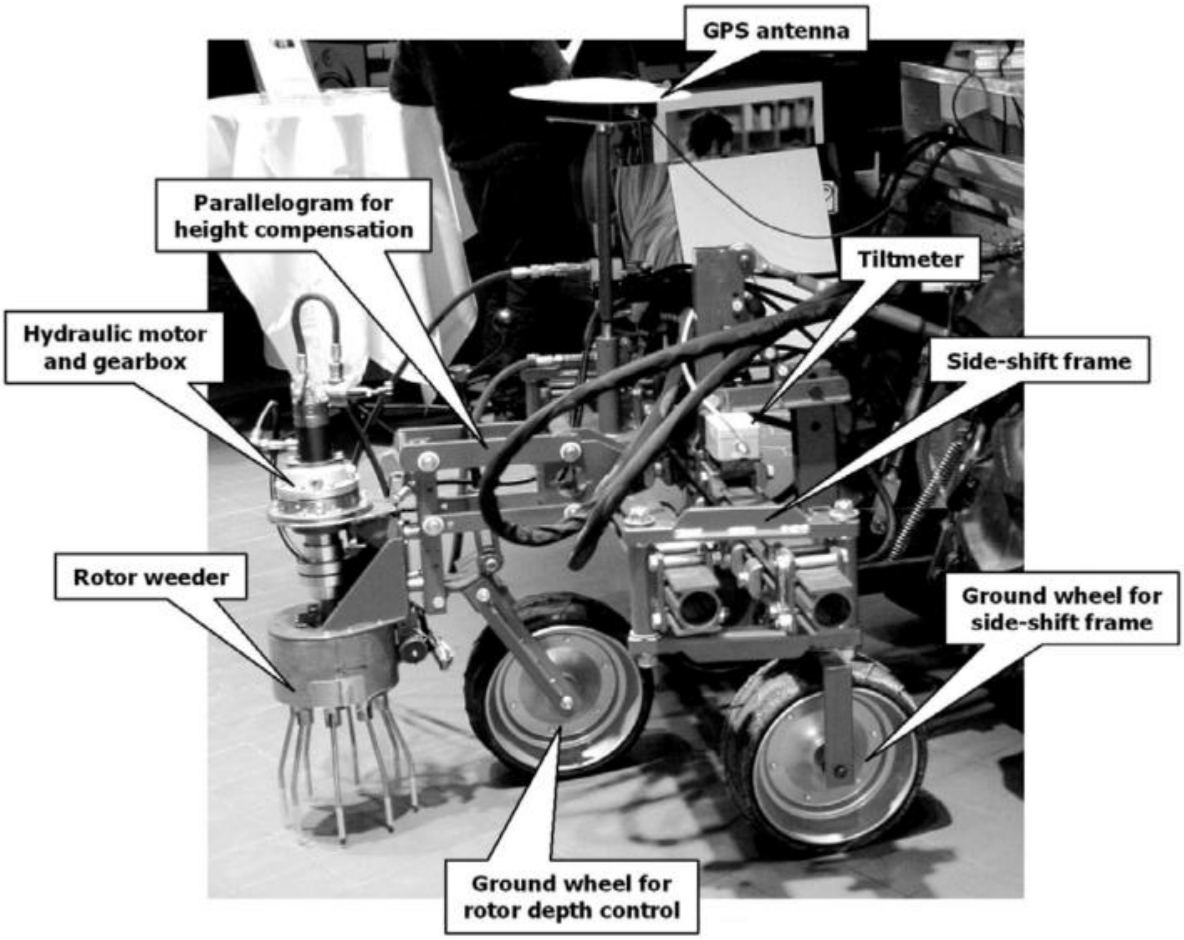


Figure 2.12: Rotor tine weeder, also known as cycloid hoe, includes a side shift mechanism for lateral control and ground wheel for depth control (Griepentrog et al., 2006).

Chapter Summary

From the literature that was reviewed, it can be concluded that:

1) In general, the weed control performance of mechanical weeders ranges from 60 – 80% reduction in number of plants.
2) The depth used for current non-automated mechanical intra-row weeding devices ranges from 1 to 2 cm (0.4 to 0.8 in.).
3) The forward speed during non-automated mechanical intra-row weed control is from 0.7 km/h to 9.7 km/h.

Although the performance of current non-automated mechanical weeding technology seems promising, there are some other issues that should be considered. Machines such as the finger weeder and the torsion weeder require very accurate steering to minimize crop damage. Brush weeders, although they have very good performance, require an operator at the rear to move the brushes in and out of the crop row. The more advanced vision-based weeders require slow forward speeds with a larger plant spacing to ensure good weed control.

Further research into the brush weeder concept of weed control has not been reported. Automation is a natural next step for this concept since it has produced good weed control efficacy. In addition, automation can help reduce issues such as labor costs and availability in regards to mechanical weed control.

Current automated weeding machines have not used electrical power for the weeding mechanism. Mechanical and fluid power has been widely used for controlling the weeding actuators. By using electric and electronics, it is hypothesized that more precise control of the weeding actuators can be accomplished. Also, the power consumption of the system can be monitored to understand the effect of soil depth, actuator speed and other factors on required power. Electrical systems do not leak and cause soil contamination like hydraulics systems which is prone to have hydraulic fluid leakage.

CHAPTER 3. INTRA-ROW WEEDER DESIGN PROCESS

From the literature review outlined in Chapter 2, several important designs and requirements were captured. This chapter contains the design process of developing the intra-row weeder. The design process started out by listing out the design goals and choosing the weeding mechanism by analyzing and discussing several design concepts. The design requirements for other components of the intra-row weeder were discussed, including the weeder frame and the weed control mechanism and actuation system. A mathematical model was developed and analyzed using system parameters to understand the kinematics and dynamics of the weeding mechanism. The first prototype was built and tested. Revisions and modifications were done to the design. A new pivoting arm concept was developed, discussed and fabricated. A simulation of the tine rotary motion was developed to obtain estimation on how different number of tines will affect the tine working width. All of this information was important in developing the automated intra-row weeder.

To start out the design process, several design goals and requirements for a weeder were set.

- The weeder will be designed for intra-row weeding of vegetable crops, since weed control in the intra-row region is challenging for mechanical weeding systems and has good potential for automation technologies
- The weeder will be targeted for small scale vegetable crop production, since it will only have two actuators that will operate on the same crop row.
- The weeder will be targeted to achieve intra-row weed control efficacy of 80% or more reduction in the number of living weed plants after a weeding operation, since the literature shows that mechanical weeders can obtain this range of efficacies.

- The weeder should be able to control weeds with minimal crop plant damage.
- The weeder will be designed to target early growth stage weed control, because weeds are easy to discriminate at early growth stages.
- Overall dimensions of the weeder must not too bulky, as it will operate only in the area in and around one crop row.
- The weeder can be pulled using a small tractor (e.g. 40 kW) because it is does not require any power from the tractor and is not too big.
- The weeding mechanism will be powered electrically instead of using fluid power because of the hypothesis that the weeding operation can be accomplished with lower power levels than previously tested.

Design Constraints of the Developed Prototype

During the design process, we have also decided on the following design constraints for our prototype:

- This prototype will only work in cultivated fields with well tilled soils.
- This prototype will target small scale vegetable farms, which means that the work rate will be lower compared to larger, bulkier machinery targeting large scale production.

Design Concept

Several concepts were considered for the mechanism to perform weed control. The design requirements for choosing the weeding mechanism were:

a) An effective weeding mechanism should be able to uproot, bury and cut weeds at the same time.

b) The working diameter of the weeding mechanism should be as small as possible to operate within the crop row.

c) The weeding mechanism should not be required to work at a depth more than 50.8 mm (2 in.) because early growth stage weeds have not penetrated deeply into the soil.

Four weeding mechanism concepts were considered as design alternatives:

1. Saw-teeth mechanism

   This mechanism uses rotating circular saw blades (hole-saw) attached to and rotated by a vertical shaft. In the presence of weeds, the mechanism would be lowered into the soil to destroy weeds (Fig. 3.1a). The small size of the weeding mechanism makes it possible to move in and out of the crop row easily. However, it might not produce a good effect of weed control because although it would easily penetrate deeper into the soil, it would require lots of force to move the weeding mechanism either laterally or in the forward direction.

2. Flat blade mechanism

   This mechanism uses flat blades that are mounted to a vertical shaft and oriented horizontally. In the presence of weeds, the rotating mechanism would be lowered into the soil. This mechanism is similar to the ones used in mobile, backpack weeders or weed-eaters (Fig. 3.1b). This concept is very effective for cutting weeds, but not effective for burying and uprooting weeds. It would only cut weeds at the soil surface.

3. Nylon brush mechanism

   This mechanism uses multiple nylon brushes attached to a disc (Fig. 3.1c). With this concept, the mechanism can have more contact with the weeds, making it a good potential for high weed control efficacy. It would also perform burial and uprooting operations on the weeds, as well as sweeping the weeds from the soil. This concept would require low rotational speeds because it has more mechanism surface area in contact with the soil than other weeder alternatives. However, due to the sweeping effect, this concept would create more dust, especially in dry soil conditions.

4. Flexible tine mechanism

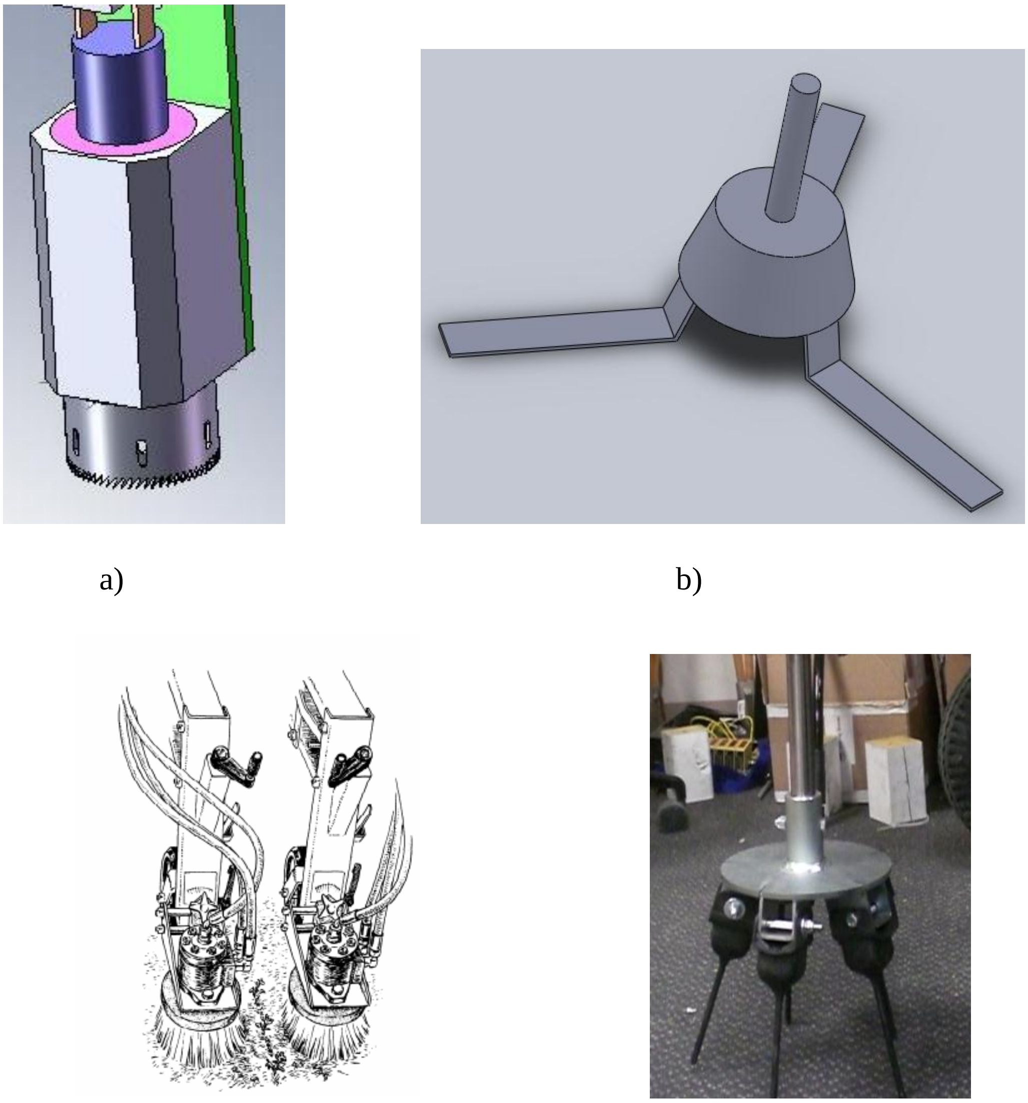
   This mechanism uses several flexible steel tines attached to a disc and oriented vertically or 10 to 20 degrees off the vertical plane (Fig. 3.1d). This mechanism is able to uproot, bury and cut weeds as it rotates. The rotational speed requirements depend on the number of tines used, whereas increases in the number of tines will decrease the speed requirement. This mechanism is similar to the nylon brush mechanism, except that it uses a small number of steel tines, which can reduce dust produced during operation.

A decision matrix was developed to look at the different mechanisms with specific criteria (Table 3.1). The criteria to choose the most suitable mechanism were ability to cut weeds, ability to uproot weeds, the ability to bury weeds, the ability to create less dust, ability to work up to 50.8 mm soil depth and easy maneuverability. From the decision matrix, it was shown that the flexible tine mechanism is the best choice because it met all the six criteria. The nylon brush met five criteria, but the requirement to create low dust levels could not be met. This was due to the sweeping effect of the brushes that would create a lot of dust in dry soil conditions. The saw teeth mechanism did not meet two criteria, which was ability to uproot weeds and easy maneuverability; because this mechanism would require a large force to move the weeding mechanism laterally once it has penetrated deeply into the soil. The flat blade mechanism had the least amount of criteria met, with only three criteria. This mechanism could not uproot or bury weeds because it only operates on top of the soil to cut weeds.

Table 3.1: Design decision matrix to choose the most suitable mechanism to be used on the intra-row weeder based on six criteria.

	Mechanism			
Criteria	Saw teeth	Flat blade	Nylon brushes	Flexible tines
Ability to cut weeds	✓	✓	✓	✓
Ability to uproot weeds	X	X	✓	✓
Ability to bury weeds	✓	X	✓	✓
Ability to create less dust	✓	✓	X	✓
Ability to work at 50.8 mm soil depth	✓	X	✓	✓
Easy maneuverability	X	✓	✓	✓

After considering these concepts, the flexible tine mechanism concept, similar to that used by the ECO weeder, was pursued because it would produce less dust compared to nylon brushes like those used by brush weeder referenced in Chapter 2. Not only can it penetrate more deeply into the soil, it can cut, uproot and bury weeds at the same time. Rotating weeding mechanisms were viewed highly because of advantages observed with the brush weeder using rotating brushes.



a) b)

c) d)

Figure 3.1: Different types of weeding mechanisms considered to be used for weed control. a) saw teeth b) flat blades c) nylon brushes d) flex tines.

In Chapter 2, the brush weeder and ECO weeder were identified as having the ability to uproot, cut and bury weeds and could achieve a weed control efficacies of 60-80% of the weed plants removed at a forward travel speed of 1.6 to 4.8 km/h. However, the brush weeder concept described in the literature required an operator to control the movement of the brushes in and out of the crop row (Cloutier et al.,2007; Melander, 1997; Fogelberg and Gustavsson, 1999; Kouwenhouven, 1997). In the research project documented by this thesis, the movement of the flexible tine weeding mechanism was to be automated instead of relying on an operator controlling the brushes. The brush weeder described in (Cloutier et al., 2007; Melander, 1997; Fogelberg and Gustavsson, 1999; Kouwenhouven, 1997) used hydraulics to rotate the brushes. In this research, an electrical motor system was used to rotate the flexible tines. As mentioned in the previous chapter, there were several reasons that an electrical system was chosen over hydraulic system including specifically:

a) Electrical systems have a faster response compared to hydraulic systems
b) Electrical systems can be more precisely controlled compared to hydraulic systems
c) The electrical power consumption can be easily monitored when using an electrical system to understand the effect of soil depth, actuator speed and other factors on required power.
d) Electrical systems do not leak and cause soil contamination.

To move the tines in and out of the crop row, another motor will be used to control the lateral motion of the brushes. By replacing an operator with an automated system to control the tine movement, a good crop and weed detection system is required. A machine vision system will be included in the system to differentiate between crop plants and weed plants, to command the tines to move in a lateral motion avoiding the crop plants. However, due to the scope of this thesis, the vision system will not be discussed. The design requirements for each main component are discussed.

Weeder Chassis

In designing the weeder chassis, a few considerations were made:

1) The overall width dimensions of the main frame must cover one crop row. This dimensional requirement is to ensure that each brush can operate on each side of

the crop row. Also, a vision system must be mounted on the main frame for crop-weed detection.

2) The overall width of the machine must allow it to fit within the row spacing of most vegetable crops and within the tread width of most small tractors (40 kW).
3) The overall length should be sufficient to mount the mechanical weed control actuation system as well as the machine vision system.
4) The ground clearance should be sufficient to ensure that the prototype can go over the crop row. The suggested crop height should not be more than 30 cm, because small tractors usually have a ground clearance of around 30 cm. Since electrical components will be included in the frame, a height far away as possible from the soil is recommended so that soil and debris will not damage anything.
5) The main frame should have a mechanism to ensure constant contact between the rear tires and soil surface even when the soil surface is uneven.

Weed Control Mechanism and Actuation System

A major design effort was devoted to the design of the weed control mechanism and actuation system. This system is the major focus of the thesis. In designing this system, the following considerations were taken into account:

1) There should be two actuators, one on each side of the crop, to remove or damage weeds plants on the left and right side of each crop row.
2) For weed control, an electric motor with high torque at low speeds should be used. For electric motors, there are two known types that could be used, stepper motors and servo motors. Stepper motors use multiple teeth-shaped electromagnets, or pole stators, arranged around a rotating central gear that will move teeth by teeth, or steps, according to which pole stator that is switched on. It is usually used for precise

positioning. Servo motors are electric motors, normally DC, which include a permanent magnet assembly with a central rotating commutator that receives current. This current will pass through the magnets creating a magnetic field and which causes the commutator to rotate and produces torque which then turns the motor shaft. Since we have decided to use an electrical system for the weed actuation system, a DC servo motor was chosen instead of a stepper motor because of the reasons below:

a) Servo motors have higher efficiency compared to stepper motors because stepper motors consume substantial amount of power, even without load.
b) Servo motors use closed loop system which means that the motor system includes feedback for data such as speed control and positioning. Stepper motors incorporate open loop system whereby the controller will give a command to rotate at a certain speed, without knowing the actual speed with a certain load.
c) Servo motors can generate high power output even with its compact size while stepper motors can only generate low power for its size and weight.

In determining the most suitable DC servo motor, we looked at two types, the brush DC motor and the brushless DC (BLDC) motor. Brush DC servo motors are typical DC servo motors where a commutator attached with brushes rotate in between permanent magnets. In BLDC motors, as the name designates, replace the rotating movement of the commutator brushes with a rotating permanent magnet rotor, using external switches synchronized to the rotor’s position. We decided to use BLDC motors instead of a brush DC motor because of the following reasons:

a) Brush DC motors require more maintenance, since the brushes that press against the commutator must be replaced at regular intervals. The BLDC motor does not require this type of maintenance because it does not use brushes.

b) BLDC motor can generate more power in a compact size compared to brush DC motors.

3) To replace an operator controlling the brush location relative to the crop row, linear sliding motion system was chosen. Griepentrog et al. (2006) have investigated a similar concept, but used hydraulics to move the actuator sideways. There are a lot of options for linear slide motion, but only two were considered: a lead screw drive or a belt drive. A lead screw drive is a long threaded shaft called translation screw that translates turning motion into linear motion. Belt drive however use rubber belt connecting at least two pulleys at opposite ends A belt drive was chosen instead of a lead screw drive because:

a) Linear belt drives can be driven at high speeds compared to linear lead screw drives. While lead screw drives cannot offer high speeds, it can produce higher precision.

b) Linear belt drives require less maintenance because it uses a rubber belt-pulley system with low friction while lead screw drives require high maintenance because of the metal friction at the screw threads.

c) Linear belt drives are more efficient than lead screw drives due to the low friction involved.

4) To move the weed actuation system in a lateral motion at a very high speed, we needed to ensure that the actuator assembly was as light as possible. To achieve this, we mounted the BLDC motor on the weeder main chassis rather than on the lateral motion assembly. A flexible shaft was used to transmit power from the BLDC motor to the rotor tines.

5) Down pressure control was also taken into consideration to be self-adjustable. A spring mechanism would likely to ensure that the weeding mechanism will maintain contact with the soil.
6) Support rails should be added for the lateral motion assembly to ensure the structure can withstand any external forces and also to enhance the actuator's strength.

Mathematical Model of the Actuation System Kinematics

The design concept of the actuation system is that whenever the vehicle approaches a crop plant inside a crop row, the lateral motion actuation system will move the weeding mechanism away from the crop row, at the same time it will perform weed control in the area adjacent to the crop row. When the weeding mechanism passes by the crop plant, it will move back to its origin position, near the centerline of the crop row.

To understand the kinematics of the actuation system, a model of the actuation system was developed (Fig.3.2). The small circle on the left represents the shape of the tine weeding mechanism with a radius of r_{tool}. The big circle on the right represents the crop canopy with radius r_{canopy}. The dashed circle on top is the position of the weeding mechanism after it moves away from the crop canopy. *S* represents the forward motion distance traveled of the weeding mechanism from its initial position while *y* represents the lateral distance. *Theta* is the angle of departure from the forward vehicle travel direction. The triangle connecting the centers of all the three circles is used to derive the mathematical formulation for the model.

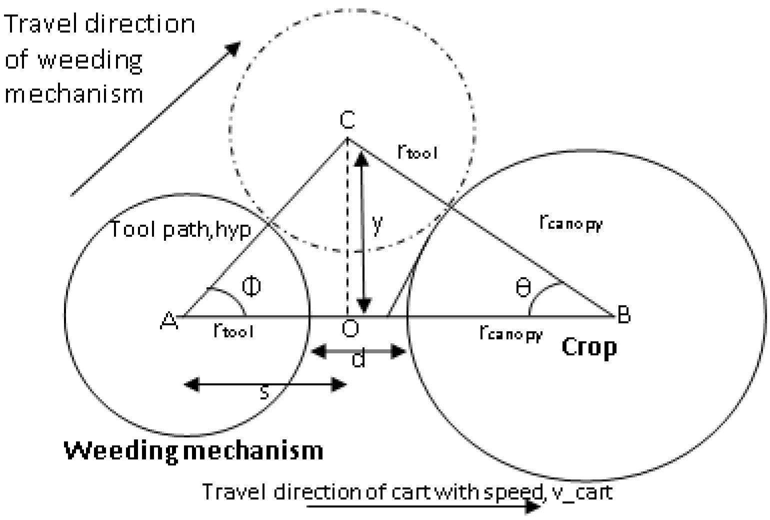


Figure 3.2: Mathematical model developed to investigate the system dynamics and kinematics using variables *hyp*, r_{tool}, r_{canopy}, *s*, *d* and v_{cart}.

The horizontal line represents the crop row centerline. The weeder will enter a crop row, at a forward speed, *v_cart* and be guided at the center of the crop row. At a departure distance, *d*, the actuation system, or tool, will be commanded to move diagonally from A to C. The horizontal distance the tool moved, *s*, is the forward distance travelled by the actuation system. The actuation system has a radius, r_{tool}, and the crop canopy has a radius, r_{canopy}.

The distance OB is given by

$$OB = \frac{d}{2} + r_{canopy} \tag{1}$$

The angle of the actuation system with respect to the center of the crop canopy, θ, in radians, is given by

$$\theta = cos^{-1} \frac{\frac{d}{2} + r_{canopy}}{r_{tool} + r_{canopy}} \tag{2}$$

The vertical distance of the actuation system from A to C, *y*, in m, is given by

$$y = (r_{tool} + r_{canopy}) sin\, \theta \tag{3}$$

The horizontal distance of the actuation system from A to C, s, in m, is given by

$$s = r_{tool} + \frac{d}{2} \tag{4}$$

The diagonal distance from A to C in m, *hyp*, is given by

$$hyp = \sqrt{(s)^2 + (y)^2} \tag{5}$$

Therefore, the time, *t*, in seconds, taken for the actuation system to move *s* distance, assuming that the travel speed is constant, is:

$$t = \frac{s}{v_{cart}} \tag{6}$$

where v_{cart} is the forward speed of the weeder chassis, in m/s.

The angle CAB, represented by φ can be calculated by

$$\tan\varphi = \frac{y}{s} \tag{7}$$

which can be used to obtain the vertical velocity in the direction of *y*, in meters per second:

$$v_y = v_{cart} \tan\varphi \tag{8}$$

Kinematic Analysis

To estimate the soil forces that will be acting on the actuation system, a single tine soil dynamics model developed by Godwin and Odogherty (2007) was used. This model was based on the work from Godwin and Spoor (1977), Godwin et al., (1984) and Wheeler and Godwin (1996). The model has been implemented in a spreadsheet that calculates the draft and vertical forces acting on a single tine working in soil. The soil parameters used in this model were soil bulk density, cohesion, internal friction of angle, surcharge and interface friction angle. The tine parameters used for this model were tine working depth, tine width, rake angle and velocity. The rupture distance ratio, m, which is the ratio of forward soil rupture distance over critical depth, was calculated from an empirical relationship. The N factors are dimensionless numbers that were obtained by interpolation of rake angles, ranging from 20 to 130 degrees and soil internal friction angle (ranging for 0 to 45 degrees). The calculation of the soil forces acting on the tine was accomplished by finding the values of passive force, P; the tine width of the crescent flanks of the soil failure pattern, W; the lateral passive force, S; and the lateral failure force, Q, using the following equations,

$$P = \gamma {d_c}^2 N_\gamma + c d_c N_{ca} + q d_c N_q \tag{9}$$

$$W = w + d_c(m - (m - \frac{1}{3}) \tag{10}$$

$$S = \gamma v^2 N_a d_c / g \tag{11}$$

$$Q = \frac{wcN_c}{d-d_c} + \frac{0.5(1-sin\phi)\gamma w N_q}{d-d_c} \tag{12}$$

where γ is the soil bulk density, in kN/m^3; d is the working depth, in m; d_c is the critical depth, in m; cohesion is the, c in kN/m^3; q is the soil surcharge, in kN/m^3; w is the tine width, in m; m is the rupture distance ratio; g is the gravitational acceleration, in m/s^2 and ϕ is the internal friction angle, in degrees. All N are obtained by interpolation of rake angle, α in degrees.

From which the draft force (D) and the vertical force (F) can be obtained by

$$D = \left(PW + S(w + 0.6d_c)\right) \sin(\alpha + \delta) + Q + c_a w d_c \cos(\alpha) \tag{13}$$

$$V = -((PW + S + (\mathrm{w}{+}0.6d_c)) \cos(\alpha + \delta) + c_a w d_c \sin(\alpha) \tag{14}$$

where P is obtained from (9), W is obtained form (10), S is obtained from (11), and Q is obtained from (12) and where α is the tine rake angle in degrees; c_a is the soil-interface adhesion, in kN/m^3; and δ is the interface friction angle, in degrees.

Using the spreadsheet containing the tine model, the required draft force for a 90 degree rake angle tine moving at lateral velocity obtained in (8) was estimated. Because there was no actual soil data available, the soil parameters for both frictional soils and cohesive soils, provided by Wheeler and Godwin (1996) were used for this simulation. The draft force did not change significantly between different velocities, but there were differences between different soils (Fig. 3.3). For this simulation, an average value of the maximum force from both soils was calculated. As a result, a draft force of 40 N was obtained. For the modeling, a weeding mechanism with 3 tines was chosen, so the total draft force was 120 N.

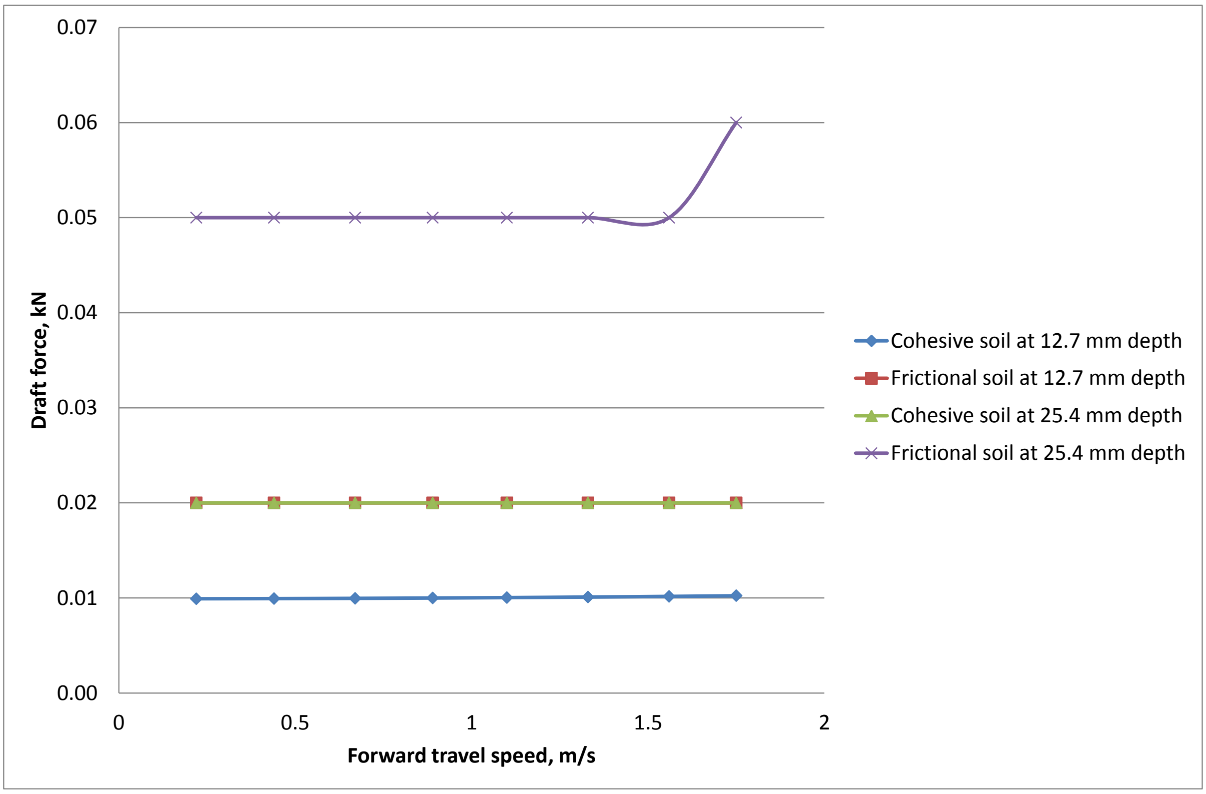


Figure 3.3: Draft force of cohesive and frictional soils with different travel speeds.

The maximum force, F_{max}, required is obtained by the magnitude of the soil force, F_{soil}, in the vertical and horizontal planes. This is calculated as

$$F_{max} = \sqrt{F_{v\_soil}^2 + F_{h\_soil}^2} \quad (15)$$

The required acceleration to move the actuation system laterally, to overcome the lateral soil draft force and the rotational force is

$$a = \frac{F_{max}}{m} \tag{16}$$

where F_{actual} is obtained from (15) and *m* is the mass of the actuation system.

An integrated servo motor was chosen to drive the lateral motion actuation system. In order to select the right motor specifications, the power and torque of the system had to be calculated. The torque of the system, *T*, in Newton-meters (N m) was calculated using

$$T = F_{max}\frac{d}{2} \tag{17}$$

where d is the diameter of the belt pulley, in meters(m).

The motor speed, N, in revolutions per minute (rpm), could be obtained by

$$N = \frac{30v_y}{(d/2)\pi} \tag{18}$$

where d is the diameter of the belt pulley, in meters(m) and v_y is obtained from (7).

Therefore, the motor power required for this system, P, in Watts (W) could be obtained by using the formula below:

$$P = \frac{TN}{60} \tag{19}$$

The time, t_d, in seconds (s), for the weeding mechanism to move laterally after crop-weed detection could be obtained by

$$t_d = /v_{cart} \tag{20}$$

where *d* is the departure distance, in m and v_{cart} is the lateral velocity, in m/s.

Analysis of System Parameters Using Model

The system parameters were analyzed using the model developed above. This analysis was important to ensure the components selected met the requirements of the system. The analysis was done over a range of vehicle forward speeds from 0.8 km/h (0.5

mile/h) to 6.4 km/h (4 mile/h). The departure distance, which was the distance before the weeding mechanism will move away from the crop canopy, was also taken into consideration. The departure distance used in the analysis was from 10 mm to 40 mm.

The parameters values that were estimated were:

i) The lateral velocity for to move the actuator assembly.

ii) The torque required by the linear belt drive servo motor.

iii) The required motor speed to drive the actuator assembly.

The system parameter analysis model was developed using Matlab script. The input parameters were m_{sys}, F_{soil}, r_{tool}, $r_{canopy}$and d. From these values, it was possible to analyze the system.

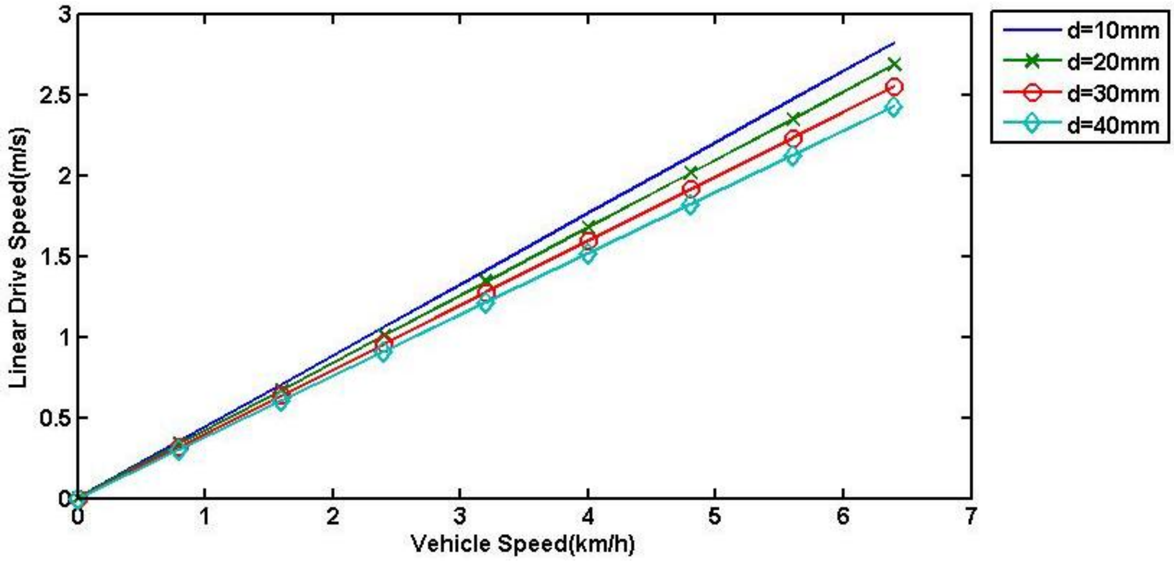


Figure 3.4: Required linear drive speed (m/s) of lateral motion actuation system using different vehicle forward speeds (km/h) and different departure distances (mm). High linear speed is required when vehicle speed is increased.

The linear speed required four different forward speeds in km/h and different departure distances from the crop were analyzed (Fig. 3.4). If the departure distance was closer to the crop canopy, higher linear speeds were required. As the prototype moves forward at a higher speed, the linear speed requirement also increased. From this figure, it showed that targeting faster vehicle speed was not achievable, because of the high linear speed requirement.

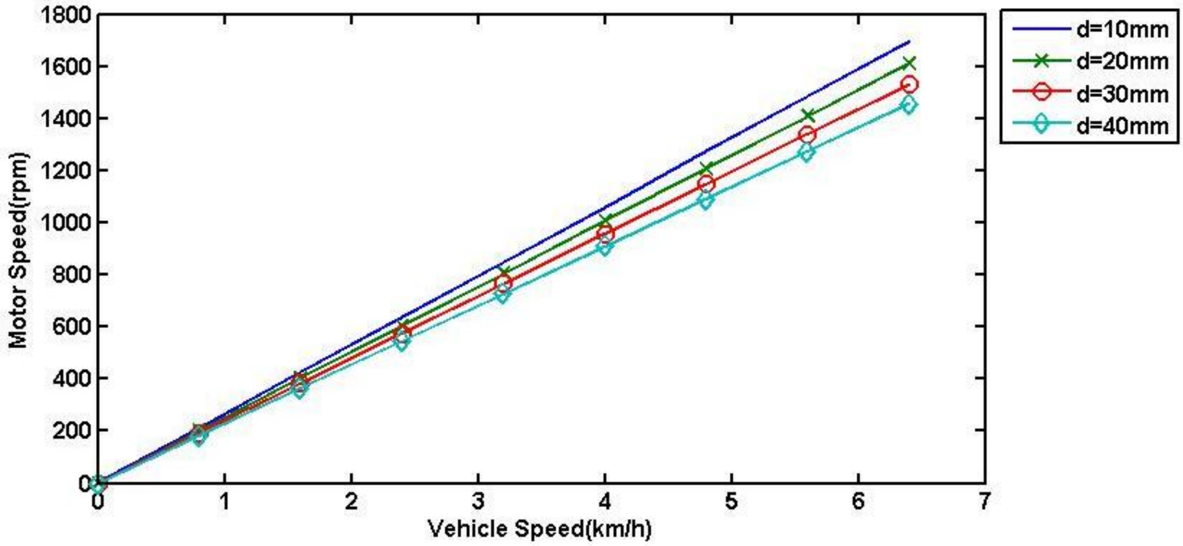


Figure 3.5: Required linear belt drive servo motor speed (rpm) of lateral motion actuation system using different vehicle forward speeds (km/h) and different departure distances (mm). High speed is required to move the weeding mechanism assembly at higher vehicle travel speeds.

Using the assumption that the linear belt drive servo motor is able to instantaneously accelerate the system, the required speed for the linear belt drive servo motor to move the weeding mechanism assembly was analyzed (Fig. 3.5). The output graph shows a linear relationship between the speed required by the servo motor to move the weeding actuation system with the different forward speeds and different departure distances. Vehicle travel speed of more than 4 km/h would require servo motor speeds in excess of 1000 rpm.

The torque required by the servo motor to drive the actuation system was obtained using equation (17). Since the total forces remain unchanged as the velocity is increased, the torque also remains the same as the velocity is increased.

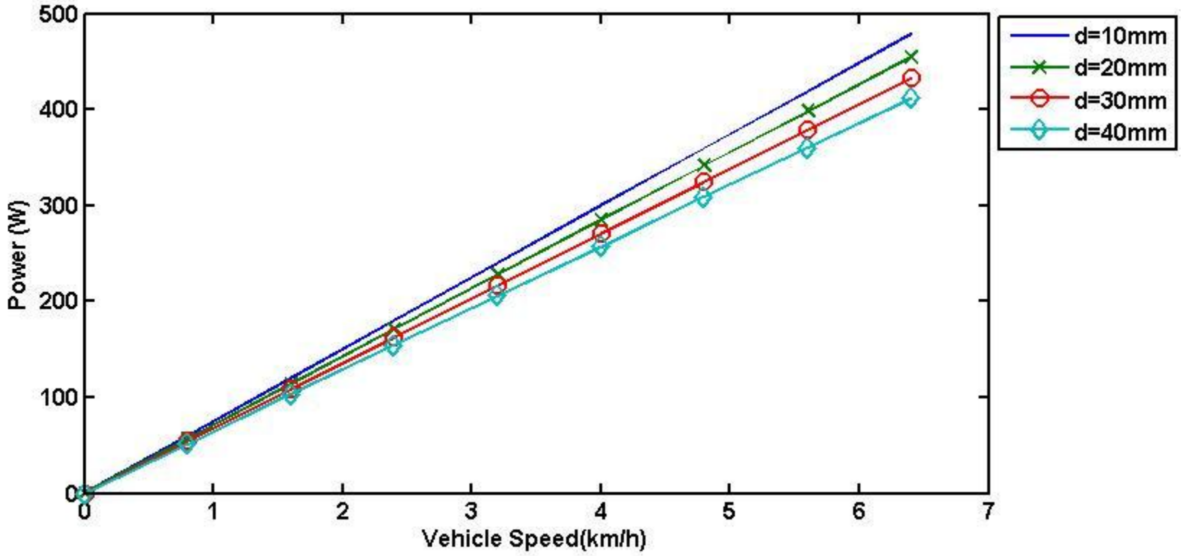


Figure 3.6: Required output power (W) of lateral motion actuation system using different vehicle forward speeds (km/h) and different departure distances (mm).

Another parameter to analyze was the power that would be required by the system (Fig. 3.6). This would also help to choose the suitable servo motor for the system. Faster vehicle travel speeds would require bigger output power of the lateral motion actuation system. However, the fastest travel speed of 6.4 km/h would only require less than 500 W of power output, at any departure distance. This parameter would be a reference value when selecting the suitable servo motor to operate the lateral motion actuation system.

In terms of real operational parameters, the time after a crop-weed is detected to move the weeding mechanism at different travel speeds is shown (Fig. 3.7). At increasing departure distance, the weeding mechanism would not require a fast response to move laterally. However, as travel speeds increases, it was shown that the lateral motion requires faster response once a crop-weed is detected.

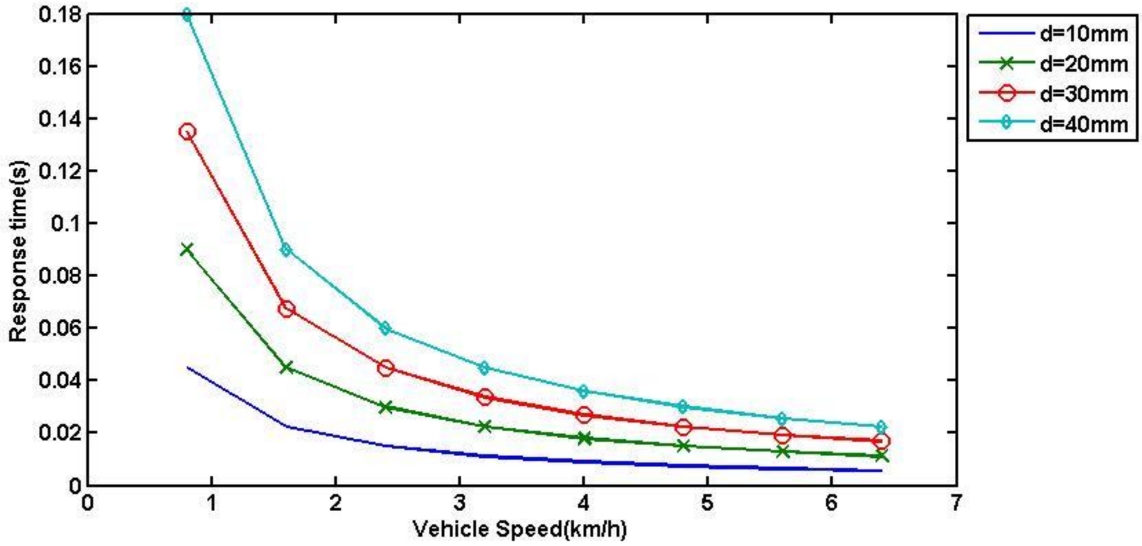


Figure 3.7: Response time (s) of lateral motion actuation system using different vehicle forward speeds (mph) and different departure distances (mm). A faster response is required for smaller departure distance and higher vehicle speeds.

Conclusions From Modeling and Simulation

The model was a useful tool to understand in detail the kinematics and dynamics of the weed actuation system. O'Dogherty et al. (2007a) and Dedousis(2007) developed kinematic simulation models for their weeding mechanism, and they pointed out that there should be a critical criteria involved in developing the kinematic simulation model. In their model, the critical criteria was the minimum distance of any point on the edge of their weeding tool from the crop center. In our model, this would be the minimum departure distance required to move the actuation system away from the crop.

From the simulation, we estimated that the minimum departure distance should not be less than 20 mm. This parameter is very important as it affects the dynamic requirements of the system.

The component selection was done based on the information gathered from the simulation model. The components that were selected based on the simulation results were:

- Linear belt drive motor

The linear drive motor chosen was an integrated servo motor (SmartMotor, Animatics, Santa Clara, CA). This servo motor has a continuous torque rating of 1.45 N m, has a no load speed of 5100 rpm, 615 W and continuous current of 15.5 A. This servo motor package contained a motor, encoder and embedded controller integrated together. It also featured an internally powered brake option which is used to automatically lock the motor from rotating when conditions such as over-current and overshoot-position occur.

- Linear drive system

The linear drive system chosen was a belt drive system (ERV80, Parker Hannifin Corp, Wadsworth, OH) that consists of teeth pulleys mounted on an 80 mm T-slotted aluminum profile to achieve precise positioning and to reduce belt slippage. The maximum travel speed that it can handle was 5 m/s and the maximum allowable drive train torque was 22.3 N m at the pulley shaft. These values were important to ensure that the weeding mechanism can move laterally at a fast speed with the desired torque.

For determining the most suitable motor to rotate the weeding mechanism, the draft force obtained using the single tine model was used. The torque required for the weeding mechanism motor was calculated using the following equation:

$$\tau = F_{soil} * r \tag{21}$$

where F_{soil} is total draft force for 3 tines and r is the weeding mechanism radius.

The targeted maximum speed of the motor was 500 rpm, based on work done by Kouwenhoven (1997) and communications with Iowa vegetable growers when using the ECO weeder. A compact BLDC motor that could handle 2 N-m and a rated speed of 3200 rpm was selected. This motor was mated to a speed reducing gearbox with 7:1 ratio to produce 14 N m of torque and motor speed of 457 rpm.

After deciding the most suitable components for the application, the design was updated to include the selected components. This was done to help reduce fabrication time.

The Intra-row Weeder Prototype

The intra-row weeder was 2.1 m long, 0.96 m wide and 1.4 m tall (Fig. 3.8). It consisted of two 40.6 cm (16 in.) swivel wheels at the front and two 40.6 cm (16 in.) fixed wheels at the rear. The front axle was adjustable in order to adapt to different field condition. There was a battery compartment near the front axles to hold up to five 12 VDC deep-cycle batteries. The estimated operating time for each battery was 120 Ampere-hour (AH). On top of the battery compartment was the data acquisition system, where an industrial computer, a motor controller and a wireless router for communication was connected and mounted on a wooden board. The actuation system of the weeding mechanism was located at the rear.

The lateral motion actuation system used a belt drive linear system to move the actuator laterally. A 48V integrated servo motor (SmartMotor, Animatics, Santa Clara, CA) attached to a 5:1 gearbox (PV34FE, Parker Hannifin Corp, Wadsworth, OH) , controlled the linear drive (ERV80, Parker Hannifin Corp, Wadsworth, OH). Support rails for the weeding mechanism were added at the top and bottom of the lateral motion actuation system. These rails were intended to reduce the forces acting on the belt drive, while distributing these forces to the support rails.

The weeding mechanism was fixed on a metal plate. The power transmission system for the weeding mechanism consisted of a flexible shaft (6426K86, McMaster-carr, Chicago, IL), a hardened hollow shaft, a coil spring and the tine weeding mechanism. The maximum torque transmission capability of the flexible shaft was 44 N-

m. The flexible shaft was connected to a 48V BLDC motor (BLY344S, Anaheim Automation, Anaheim, CA) attached to a 7:1 gearbox (GBPH0901, Anaheim Automation, Anaheim, CA), which were mounted on the weeder frame. The other end of the shaft was connected to a rotating shaft that drives the rotating tine weeding mechanism. These two shafts were connected using a shaft adapter. The rigid shaft was connected to a linear rotary bearing, which can help to reduce friction while the shaft is rotating, at the same time the shaft is moving up and down. Beneath this special bearing was a coil spring that acted as a mechanism to force the tines into the soil. At the bottom of the spring, a pillow block bearing was mounted to hold the spring in place. This bearing was mounted with special slots on the actuator plate so that it can move up and down, depending on the soil surface penetration resistance.

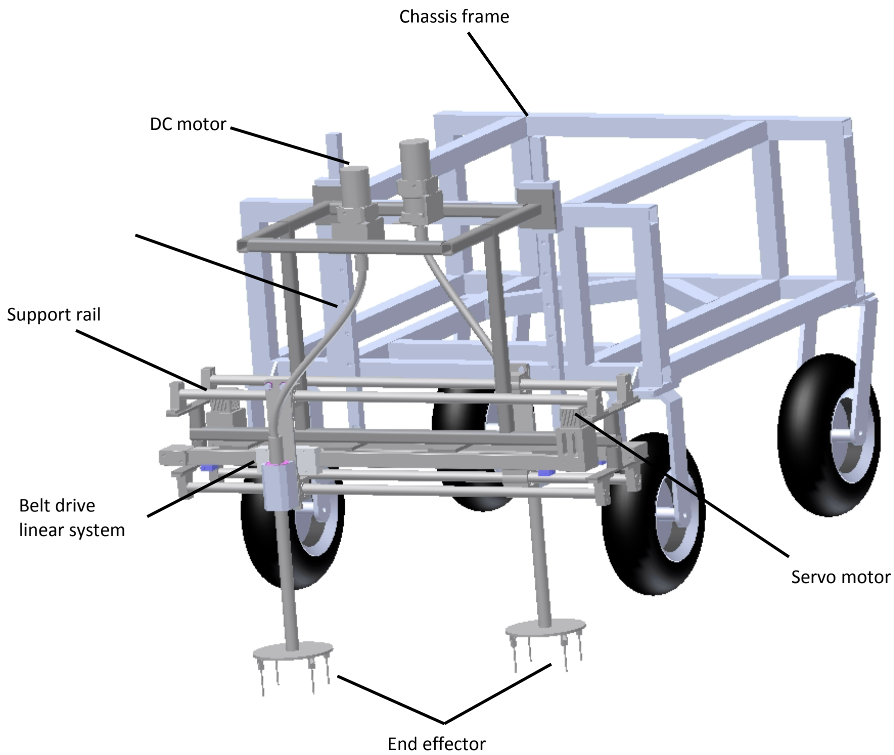


Figure 3.8: Parametric model of the lateral motion actuation system showing two weeding mechanisms operated with a brushless dc (BLDC) motor connected through flexible shafts.

Initial Performance

Initial functional tests performed in the lab indicated that the actuation system had some difficulties in moving, both in lateral motion and the rotary motion. This was due to the flexible shaft, which was positioned too high from the non-flexible shaft (Fig. 3.9). The flexible shaft was not flexible enough because it was constructed using thick metal wires that made it difficult to bend freely. This made it difficult for the motor to transmit the initial torque required to move the rotary tine weed mechanism.

There was also an issue in the actuator assembly. After assembling all the parts on the actuator plate, which was made from mild steel, we noticed that the assembly was heavy. This might affect the acceleration and the torque required from the integrated servo motor to move the actuator. The target weight of the assembly used in the simulation model was 5 kg (11 lbs.), compared to the actual weight of 6.35 kg (14 lbs.). To reduce the weight, it was better to the actuator plate was changed to a lighter and strong material.

Changes Made

Due to the problems highlighted during the functional tests, it was really necessary to make some changes into the design (Fig. 3.10). The changes that were made:

1) Changing the position of the BLDC weeding mechanism motor, from a vertical position to a horizontal position. In addition, the weeding mechanism motor was mounted on top of a spinning table, which would make it easier to move left and right, because of additional roller bearings inside the spinning table. This would also reduce the height of the weeder frame, due to the position change of the weeding mechanism motor.

2) The actuator plate was changed from mild steel to aluminum. This reduced the weight of the actuator assembly from 6.35 kg (14 lbs.) to 4.5 kg (10 lbs.).

Figure 3.9: Fabricated prototype developed positioned the weeding mechanism motor on a vertical position which made it difficult when the actuation system was moving sideways.

Figure 3.10: Improved prototype with altered position of the weeding mechanism motor and material change from mild steel to aluminum for the actuation assembly.

Field Trial

A field trial was conducted in October 2010 at the Agricultural Engineering ISU Research Farm, Ames, Iowa in Clarion soil (loam texture with 42% sand, 37% silt and 21% clay at a depth of 0 to 178 mm (0-7 in) (USDA- NRCS, 2011). The initial trial of the prototype engaging with soil showed that the flexible shaft failed to rotate the weeding mechanism. This was probably caused by several factors:

a) The soil condition which was dry and heavily compacted at the time of the trial.
b) Due to the limitations of the flexible shaft. Although the specifications stated that the flexible shaft can withhold torque up to 44.1 N m and maximum working speed of 15,000 rpm, the minimum bending radius was 17.8 cm. The bending radius was reduced when the rotating shaft was engaging the soil, and this had reduced the torque capacity, since in tighter bends the wires inside the flexible shaft rub against each other more forcefully increasing friction, heat and stress.

After several attempts to rotate the weeding mechanism, the wires inside the flexible shaft were torn and eventually failed.

Design Revision

After the experience with the field trial, we understood that the concept of using a flexible shaft would not work. The soil condition used during the trial may not represent more typical vegetable field conditions with more loose and well-tilled soil. The problems encountered caused us to re-evaluate the design and create a revised design that would still fulfill the same requirements of the research.

The same chassis was used for the revised design that used a pivoting arm concept for providing lateral motion, where this pivoting arm will swing left and right, to replace the use of a belt drive linear system. All of the motors were located near the pivot point to reduce the assembly weight as much as possible at the other end. The integrated servo motor was still be used to drive the weeding mechanism laterally. Chain drives were used to transmit torque from the integrated servo motor that would control the swinging motion of the pivot arm, as well as another chain drive to transmit power from the motor to the weeding mechanism. A rack and pinion was used to guide the swinging motion of the pivot arm.

In developing this revised design, a few considerations were made:

1) The pivoting arm moved in a circular arc motion.
2) Major components such as the integrated servo motor and the weeding mechanism motor were positioned as close as possible to the pivoting point, to ensure that at the other end it is lighter.
3) The integrated servo motor was used to swing the pivoting arm.

A chain drive system was used to transmit power from the motors, which were located at the pivoting point, to their actuators, the swinging arm motion and the tine weeding mechanism rotation. A chain drive was selected rather than a belt drive for both the pivoting arm motion and the weeding mechanism rotary motion because:

1) Chain drives are more efficient than belt drives, with an efficiency of almost 99% under ideal conditions. Belt drives are prone to slip, which reduces their efficiency, unless toothed belts are used.
2) Chain drives are more compact than belt drives. Chain drives rely on the number of sprocket teeth to reduce or increase the transmission speeds, while belt drives can only rely on pitch diameter size.
3) Chain drives are quite cost competitive relative to belt drives.
4) For the pivoting arm motion, both clockwise and counter-clockwise rotation of the drive system will be required. For this reason, the chain drive is more appropriate

because no slippage will occur and the positioning of the pivoting arm can be determined with less error.

5) The weeding mechanism required an efficient drive system to ensure that the weeding mechanism tines can perform effective weed control with minimal mechanical power loss.

Chain drive systems consist of a roller chain and at least two sprockets, a drive sprocket and a driven sprocket. These components are selected according to the ASME B29.1 standard (ASME, 2002) regarding precision power transmission roller chains and sprockets. For our application, Type B sprockets, which have a hub on one side only, were chosen and were used for both the motor providing lateral motion and the weed mechanism motor. Single strand roller chain drive was selected to drive the pivot arm and the weeding mechanism. In selecting the most suitable roller chain drives, the guidelines prepared by American Chain Association (2006) were used.

Pivoting Arm Design Requirements

The new pivoting arm concept was designed around and attached to the same prototype frame and chassis. Before deciding the best position to place the new actuation system, we determined that the future machine vision system will be located between the battery compartment and the actuation system. This location was important so that we could specify the assembly area inside the frame that would determine the crucial location of the pivot point. This pivot point was actually the rotation point of the pivot arm and everything attached to it including the weeding mechanism and the rectangular frame, which is where the integrated servo motor and the weeding mechanism motor were mounted. Based on the sprocket size selected, the width of the chain drive system of the pivot arm could be estimated. Since the limit of the lateral movement is the prototype frame width, which was 87.63 cm, a targeted working area of crop canopy radius, 15.24 cm (6 in.) was to be achieved.

With that target set, the most suitable arc radius for the rack gear was determined. This was investigated using a graphical computer simulation created using a computer-aided drafting software (Inventor Professional 2011, Autodesk, San Rafael, CA) to determine the position of the weeding mechanism shaft on the pivot arm to achieve the targeted coverage area (Fig. 3.11). The targeted coverage area defined for our design was the crop canopy diameter, which was 30.5 cm (1 ft.). This targeted coverage area was the area where the weed control would be accomplished. Many trials using different arc radii were tested to obtain the targeted coverage area. The best coverage area of 18.8 cm (7.4 in.) was obtained when using an arc radius of 64.1 cm. It was a good technique to design the crop canopy coverage to be bigger than the targeted value, since it would be very difficult to achieve a large crop canopy during actual operation because of the effect of the forward travel speed of the prototype. In addition, it would require large torque and acceleration to move the pivot arm from one end to the other.

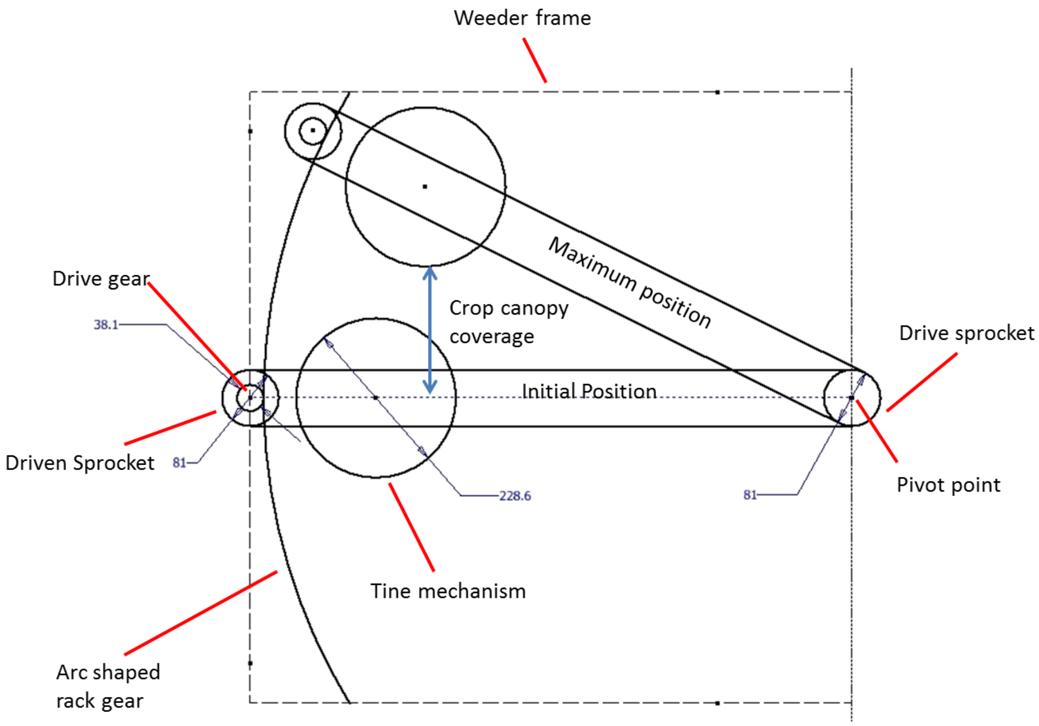


Figure 3.11: Figure of the pivoting arm concept to determine the crop canopy coverage using different arc radius of the rack gear.

After the arc radius was determined, the length of the pivot arm was determined because all of the components position attached to the pivot arm had been decided.

The mechanism to move the pivot arm used a rack and pinion concept, with the pinion gear moving along a static, arc-shaped rack gear. The selected pinion gear had a comparatively smaller diameter and number of teeth compared to the sprocket that was driving it. The sprocket was assembled on top of the pinion gear using a shaft. The reduction of size between the pinion gear and the sprocket was to ensure that the drive gear would produce a faster rotational speed than the sprockets to move the pivot arm. However, a lower torque is produced from the pinion drive gear. Since the chain drive system of the pivot arm would generate the torque to move the pinion drive gear, it would be sufficient because the pinion drive gear was carrying small load compared to the chain drive system. To ensure that the drive gear would work with the arc gear, the pressure angle and pitch of the drive gear should match with the arc gear. The pitch center diameter should always match to ensure no gear jumping.

The size of the rectangular frame that mounts the weeding mechanism motor and the pivot point was determined by the height of the weeding mechanism motor with the gearbox reducer. Adequate space was needed to install these two components to the frame. The length is determined by the location of the weeding mechanism shaft, because at one end of the frame, two tapered bearings were fixed in a special housing so that the weeding mechanism shaft would easily rotate, and at the same time resist any axial and thrust loads.

Mechanical system overview

The revised improved pivot arm mechanism was located at the rear of the weeder. The mechanism used a pivoting arm concept to move a rotating weeding mechanism laterally (Fig. 3.12).

The pivoting arm was controlled by a 48 VDC integrated servo motor (SmartMotor, Animatics, Santa Clara, CA). This motor was attached to a gearbox (PV34FE, Parker Hannifin Corp, Wadsworth, OH) with a reduction of 5:1 and was connected to a drive gear that was attached at the end of the pivoting arm, using a chain drive system. The drive gear was mated to an arc-shaped rack gear to provide the direction of the pivoting arm. This drive gear moved in both clockwise and counter-clockwise direction. This movement resulted in a left and right movement of the pivot arm.

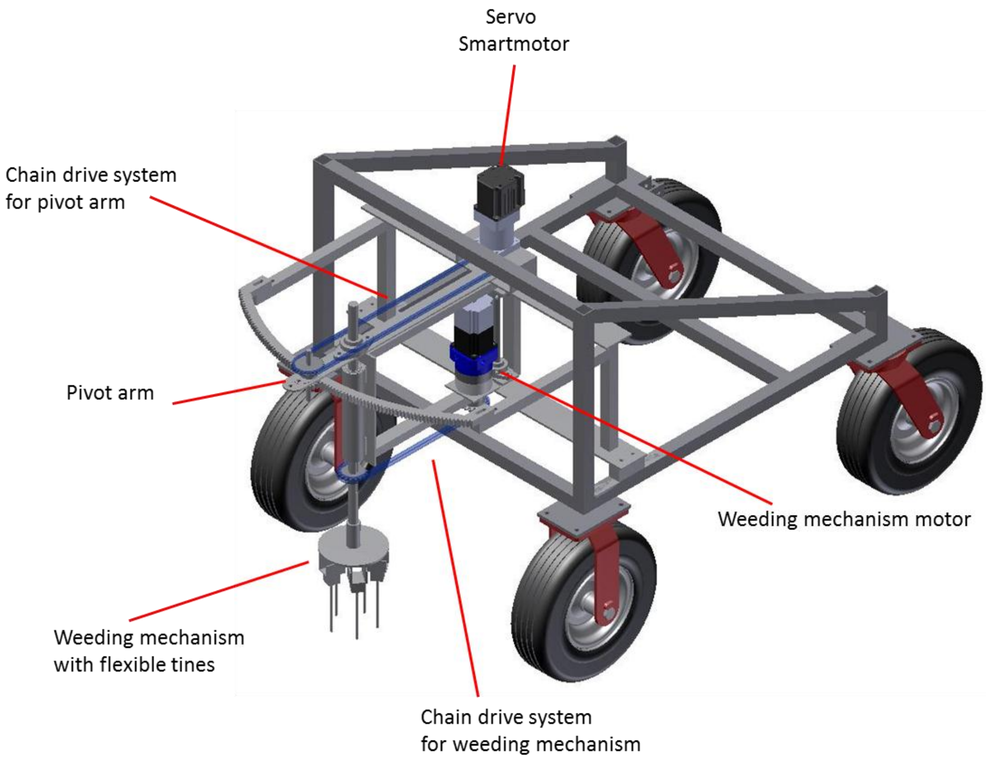


Figure 3.12: Parametric model of the weed actuation system using a pivot arm to control the lateral movement of the weeding mechanism.

The weed control mechanism was powered by a 48VDC BLDC motor (BLY344S, Anaheim Automation, Anaheim, CA). This motor controlled the speed and direction of a weeding mechanism consisting of 5 tines that engaged with the soil. This motor is controlled using an Anaheim Automation speed controller which controlled the speed and rotation direction of the motor. This motor was attached to a gearbox (GBPH0901, Anaheim Automation, Anaheim, CA) with a reduction of 7:1. This motor transmitted power to the weeding mechanism using a chain drive system. The prototype was successfully fabricated in May 2011 (Fig. 3.13).

Figure 3.13: Fabricated prototype of the weed actuation system.

Simulation of tine rotary motion

A tine kinematic model was developed to estimate how many tines paths will affect the tine working zone, which is the soil area that has been disturbed by the tine, at different travel speeds and rotation speeds. O'Dogherty et al. (2007) developed a similar model, but focused more on the kinematics of a rotating disc instead of rotating tines.

The aim of this modeling and simulation effort was to obtain the minimum required rotational speed to achieve good tillage coverage at different travel speeds. Good tillage coverage meant that the weeding mechanism tines will pass through the same area as the previous tine at least once. Due to experiences with the weeding mechanism motor being damaged, the motor current draw and power consumption were reduced by reducing the number of tines from five to three tines. The reduction was necessary to:

1) Reduce the torque required to rotate the weeding mechanism. Torque is proportional to current, the current drawn by the motor and power would be reduced.

2) Reduce the working diameter of the disc. The original working diameter was 25 cm, was considered too big to enter the working zone or the available gaps within crop plants. By reducing the working diameter by a half to 12.5 cm, the probability of crop damage would be reduced.

Tine kinematic model

The time *t*, in seconds, taken for the tine to move forward at a certain travel speed is given by

$$t = \frac{d}{v} \tag{22}$$

where *d*, is the travel distance, in meters, and *v* is the forward velocity of the weeder, in m/s.

At the same time, the tine will move in an angular direction, ψ , in radians, given by

$$\psi = \omega t \tag{23}$$

where ω is the angular velocity, in rad/s.

Tine Initial Position

The angle between each tine, θ, in radians, is given by

$$\theta = \frac{2\pi}{n} \tag{24}$$

where *n* is the number of tines.

For the tine movement, the general equations of converting polar coordinates to Cartesian coordinates were used.

For tine 1, *n* = 1, the position is

$$X_o=0 \tag{25}$$

$$Y_0= r \tag{26}$$

where r is given by

$$r = \text{weeding mechanism radius} + \text{tine radius} \tag{27}$$

For the other tines, the X_i and Y_i positions are given by

$$X_i = r \cos \phi_i \tag{28}$$

$$Y_i = -r \sin \phi_i \tag{29}$$

for the angle, ϕ, given by

$$\phi_i = (n-1)\theta - \pi/2 \tag{30}$$

Tine Moving Positions

For the first tine, the position at the next interval, t_i is given by

$$X_i = r \cos \phi + d\, i \tag{31}$$

$$Y_i = r \sin \phi \tag{32}$$

where ϕ is given by:

$$\phi_i = \frac{\pi}{2} - \psi i \tag{33}$$

and ψ is from (2) and $i=1,2,3,\ldots,i$.

For other numbered tines, the next position is given by

$$X_i = r \cos \phi_i + d\, i \tag{34}$$

$$Y_i = -r \sin \phi_i \tag{35}$$

where ϕ is given by:

$$\phi_i = ((n-1)\theta + \psi i) - \frac{\pi}{2} \tag{36}$$

Soil Working Zone Model

The model developed by Wheeler & Godwin (1996) was used as reference to estimate the working zone of the tine. The tine working zone is where soil disturbance occurs due to the tine working at a specific soil depth. When the soil is cultivated by the tine, the weeds in the tine working zone will be either uprooted, buried or cut, As a result, the weed canopy in that zone is disturbed and causes weed canopy reduction. According to (Godwin & O'dogherty, 2007), the tines used for the weeder actuation system developed by (Ahmad et al., 2011) are considered to be narrow tines, because the depth/width ratio (d/w) ratio was between 1 and 6. Using this as reference, the model (Fig. 3.14) was used. Within a certain working depth, *d*, and a certain blade width, *w*, the model showed that the working zone width is almost distance *d* to the left and the right side of the tine.

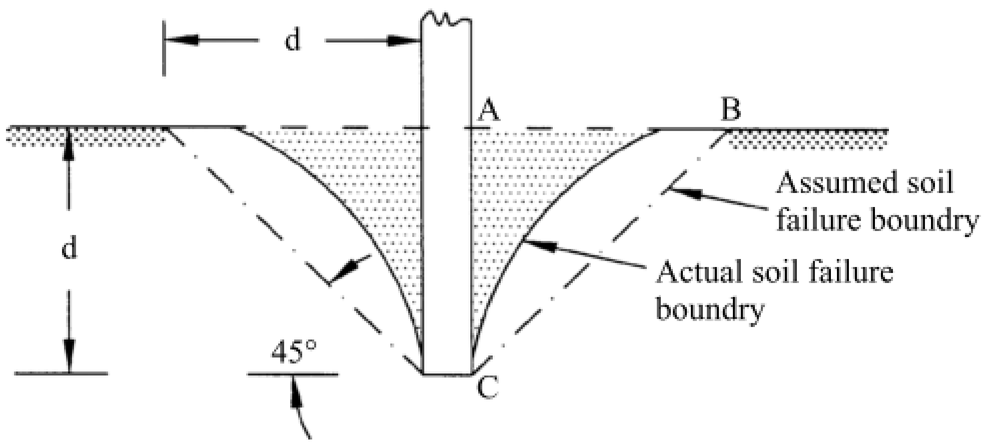


Figure 3.14: Cross-section of typical tine failure soil profile with working depth, *d* and tine width, *w* (Wheeler and Godwin 1996).

The tine was tested in an experimental plot. Using a working depth of 25.4 mm (1 in.), preliminary tests showed that the observed working zone width of the tine was only 12 mm (0.5 in.) on either side of the tine. However, this width was influenced by the dry weather and low moisture content of the soil. The distance between each tine path was targeted to be the same distance. The soil also was heavily crusted and too dry which resulted in the tines having difficulty to break into the soil.

To determine the working zone for a certain number of rotating tines, it was necessary to use predefined values for the equations mentioned above. Using a weeding mechanism with five tines, three different travel speeds (0.8 km/h, 1.6 km/h and 2.4

km/h) were tested. As indicated above, the aim was to obtain the minimum angular velocity of the tine weeding mechanism required to achieve acceptable working zones, which was either overlapping or touching between each tine.

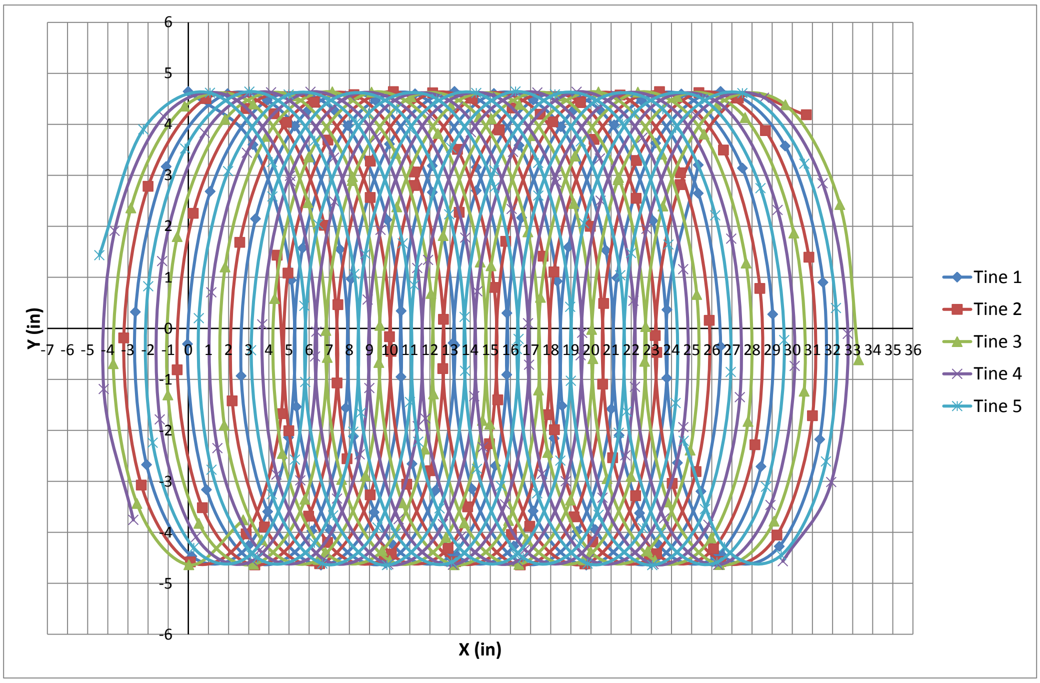
Assumptions and Limitations

1. The simulation results were only valid for the soil condition that was used during the time of the preliminary experiment. The actual working zone should be re-assessed if the tine would be used in different soil conditions.
2. The tine movements were considered moving in a perfect circular motion without any obstacles such as rocks. This condition made it easier to model.
3. Since working depth also had an influence to the tine working zone, the working depth was considered to be constant at 25.4 mm.

Simulation Results

A five tine weeding mechanism resulted in a working diameter of 22.9 cm (9 in.) for the tines. Based on the simulation results, to obtain the same distance between each tine path, rotational speeds had to be increased whenever the travel speeds were increased. The simulation was done for only a short travel distance to observe a clear view within the path distance of each tine.

When observing the slowest travel speed, 0.8 km/h, it was observed that the minimum effective rotational speed required was 200 rpm (Fig. 3.15a). When the travel speed was increased to 1.6 km/h, the minimum rotational speed required was also increased to 350 rpm (Fig. 3.15b). The fastest travel speed used for the simulation was 2.4 km/h and the minimum rotational speed required to achieve an effective weed control was 500 rpm (Fig. 3.15c).



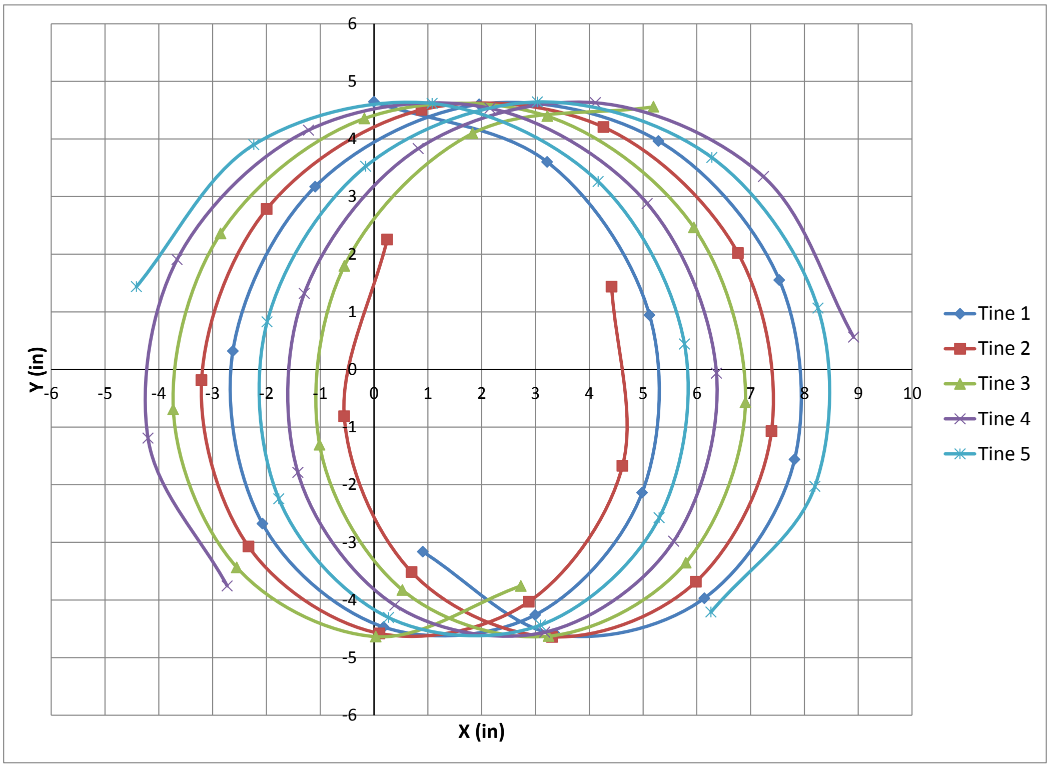
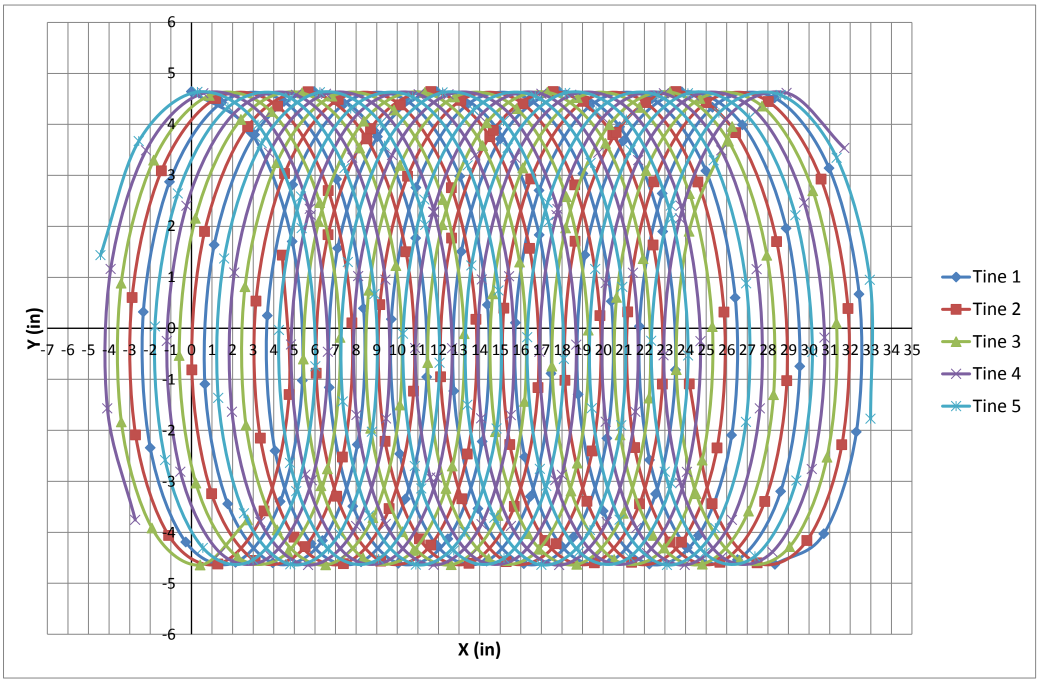


Figure 3.15a: Tine movement for 5 tines at 0.8 km/h travel speed and 200 rpm rotational speed. Top figure shows tine movement for a horizontal distance of 76.2 cm (30 in.) and bottom figure shows a detailed figure of the distance between each tine path which was more or less 12.7 mm (0.5 in.).



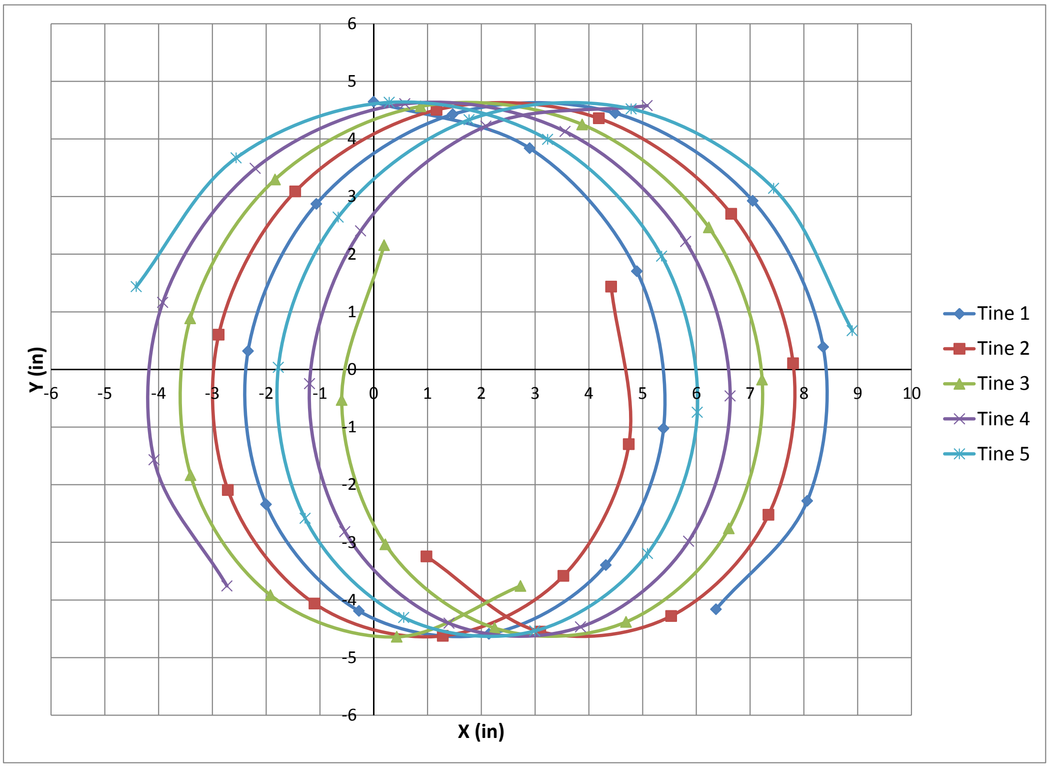
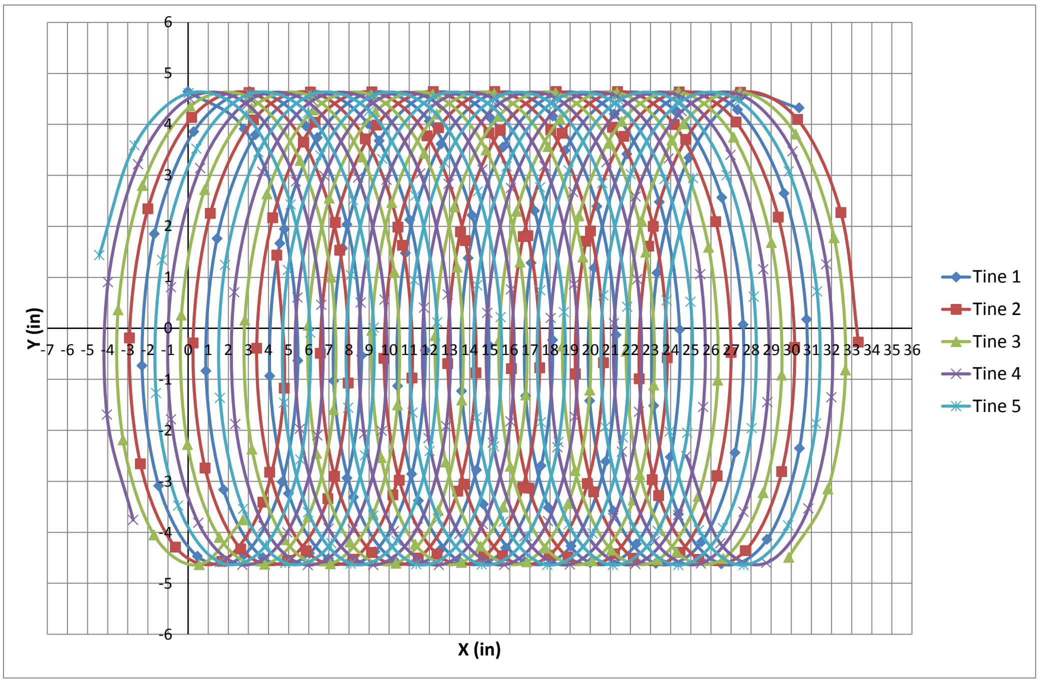


Figure 3.15b: Tine movement for 5 tines at 1.6 km/h travel speed and 350 rpm rotational speed. Top figure shows tine movement for a horizontal distance of 76.2 cm (30 in.) and bottom figure shows a detailed figure of the distance between each tine path which was more or less 12.7 mm (0.5 in.).



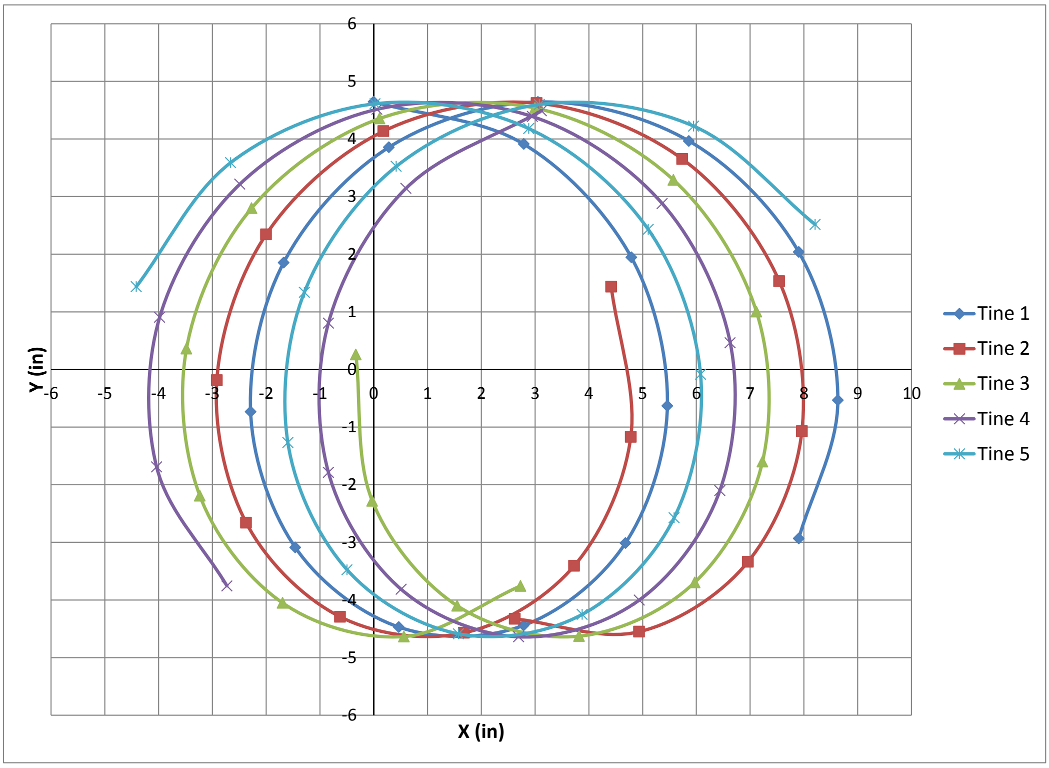


Figure 3.15c: Tine movement for 5 tines at 2.4 km/h travel speed and 500 rpm rotational speed. Top figure shows tine movement for a horizontal distance of 76.2 cm (30 in.) and bottom figure shows a detailed figure of the distance between each tine path which was more or less 12.7 mm (0.5 in.).

A three tine weeding mechanism consisting of was simulated using a working diameter of 12.7 cm (5 in.). To observe the motor speed requirements with the new set of tines, this simulation used the same travel speed and the same working depth. When the travel speed was set at 0.8 km/h, the minimum motor speed required for an effective weed control was 350 rpm (Fig. 3.16a).4. When the travel speed was increased to 1.6 km/h, the rotational speed had to be increased to 650 rpm to maintain an effective weed control (Fig. 3.16b). With the fastest travel speed available, 2.4 km/h, the minimum motor speed required was 900 rpm (Fig. 3.16c).

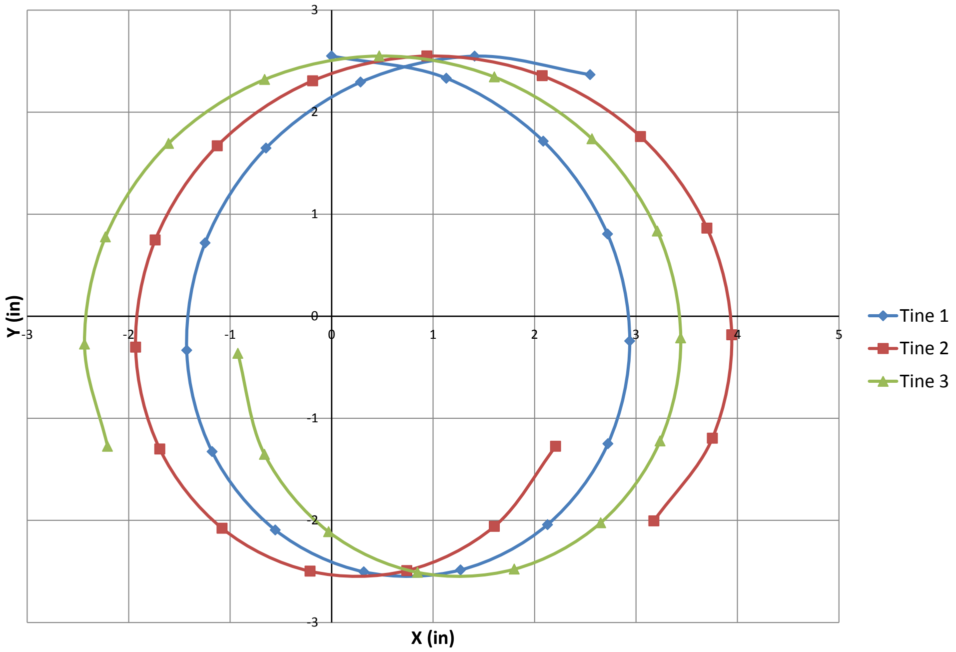


Figure 3.16a: Tine movement for 3 tines at 0.8 km/h travel speed and 350 rpm rotational speed. The distance between each tine path was more or less 12.7 mm (0.5 in.).

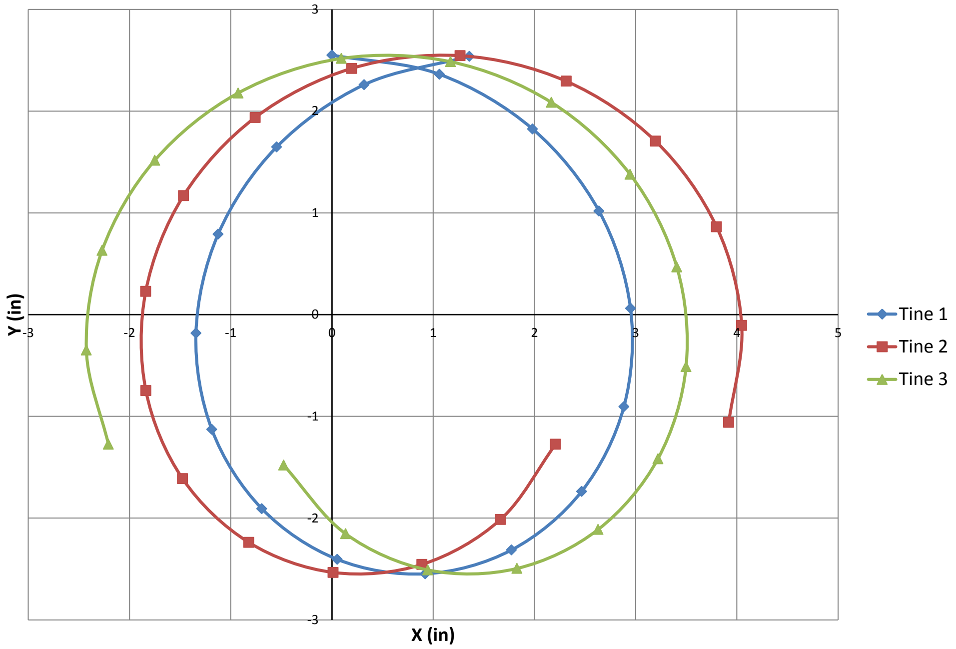


Figure 3.16b: Tine movement for 3 tines at 1.6 km/h travel speed and 650 rpm rotational speed. The distance between each tine path was more or less 12.7 mm (0.5 in.).

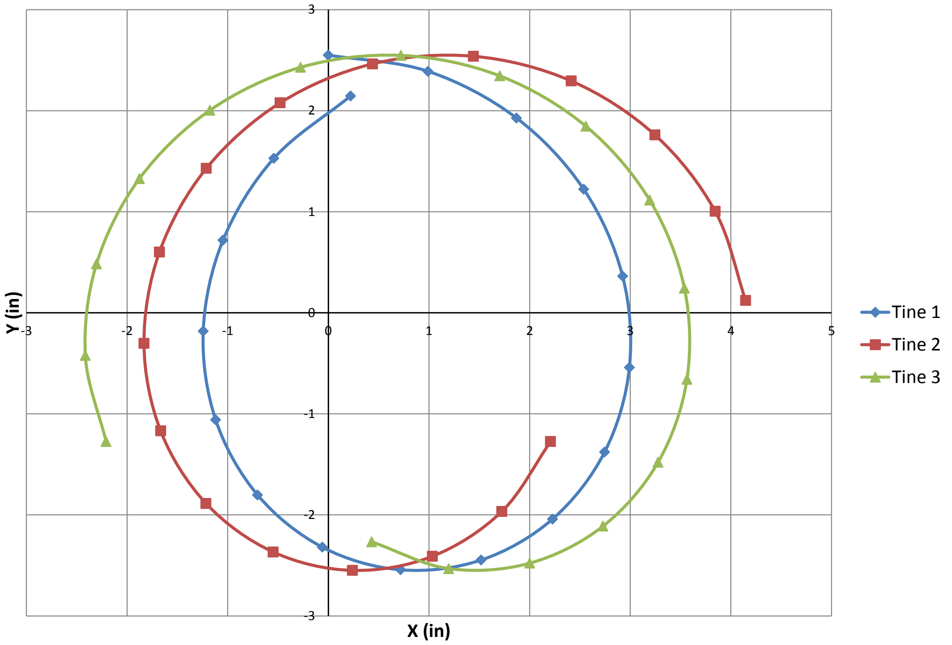


Figure 3.16c: Tine movement for 3 tines at 2.4 km/h travel speed and 900 rpm rotational speed. The distance between each tine path was more or less 12.7 mm (0.5 in.).

Due to the fact that the maximum rotational speed produced by the current weeding mechanism motor is only 400 rpm, it showed that travel speeds above 1.6 km/h were not achievable. At this point, there would be two options to choose from which was either increasing the motor speed by either using a lower gearbox reducer or purchase a new motor with higher motor speed.

Further investigation was done by conducting a field experiment based on the results using three tines. To further reduce the torque and power requirements of the actuation system, another set of tines were modified to have sharp edges at its sides. The tines were sharpened to increase the performance in uprooting and cutting the weeds. It would also assist in soil breakage. Both tine sets, the original round-type and the new sharp-type, were bent outwards 11 degrees. This was done because the modification done to the tine mount brackets of the weeding mechanism was positioned too close. The original weeding mechanism had five tine mount brackets for installing five tines. Because of the change of number of tines, modifications were done to remove all the tine mount brackets and re-position only three tines. Due to this positioning and some modification to the tine mount brackets themselves, the tine working diameter was reduced from 25.4 cm (9 in.) to 7.6 cm (3 in.). The targeted working diameter should be 12.7 cm (5 in.) to ensure enough coverage of weed area between most vegetable crops. Thus, the tines had to be modified to achieve this target.

The original plan was to use the same weeding mechanism motor used in the first prototype. However, preliminary experiments conducted during June and July 2011 showed that the weeding mechanism motor was not suitable for the application for several reasons:

1) The rated current and power of the motor were 13 Ampere (A) and 660 Watts (W). During the experiment, the motor was used more than its rated capacity for both these values. The high torque requirement from the motor led to high current

draw. Because the control system of the motor had no external fuse to prevent from high current drawn into the system, the motor malfunctioned.

2) The high ambient temperature during the experiment lowered the heat transfer rate away from the motor in which too much power was being dissipated due to the high current. As a result, the internal temperature of the motor increased to the point that the internal meltdown of the insulating material around the conductors occurred.
3) The torque required by the motor was demanding to rotate five tines with a diameter of almost 25.4 cm (10 in). As the torque value is proportional to the current of the motor, this was also another reason why the motor was damaged.
4) In one of the preliminary experiments, a heavy compacted soil caused by heavy machinery and rainfall was used to test the weeder. This resulted in a very high initial torque to be used to rotate the weeding mechanism, which meant that a large current draw was required. This also caused damage to the motor.
5) An external fuse was not installed into the control system that could have avoided this problem.

Due to these factors some modifications were done to the system to conduct a preliminary field experiment with the new version:

1) Due to the damaged weeding mechanism motor, the integrated servo motor was assembled to the existing weeding mechanism gearbox. Since both motors use the same NEMA standard frame size, which had the same square length, it was possible to just switch motors without worrying about screw holes and mounting. Although the servo motor's rated power is slightly lower than the BLDC motor, which was 615 W compared to 660 W, the speed without load was 5100 rpm,

higher than the previous motor of 3200 rpm. The continuous torque of the integrated servo motor was lower, at 1.45 Nm compared to the previous motor of 2.05 Nm.

2) The number of weeding mechanism tines was reduced from five to three. This reduced number of tines helped to reduce the torque and current requirements of the integrated servo motor to rotate the weeding mechanism tines. The reduced diameter at the tip of the tines, which was 12.7 cm (5 in.), also helped in reducing the torque requirement.
3) An additional set of tines were fabricated with a different shape. These tines were shapes with a sharpened edge parallel to the direction of rotation. It was hypothesized that this shape would assist in not only uprooting the weeds, but also in cutting the weeds and further reducing the torque and power requirements.

Chapter Summary

A prototype of a mechanical intra-row weeding actuation system was developed. The design process went through several stages before a functional prototype was made. Two designs were developed and fabricated. The main features of the first design was that it used a flexible shaft to transmit the torque from a weeding mechanism motor that was attached to the main chassis to the rotating weeding mechanism. It also included a linear belt drive system that moved the actuator assembly laterally to the crop row. The second design used a pivoting arm concept that reduced the torque requirement to move the weeding mechanism tines laterally. This pivoting arm used chain drive system to swing the weeding mechanism tines in an arc motion guided by an arc-shaped rack gear. The weeding mechanism tines were rotated using a chain drive system connected to the same BLDC motor.

CHAPTER 4. PERFORMANCE AND EVALUATION OF A ROTATING TINE WEEDING MECHANISM FOR AUTOMATED INTRA-ROW WEEDING FOR ORGANIC VEGETABLE PRODUCTION

A paper to be submitted to *The Journal of Biosystems Engineering*

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Abstract

Manual weeding operation in vegetable crop production is a laborious and tedious experience. Automated intra-row weeding is an alternative solution that would reduce these problems. A rotating tine mechanism was developed to be used as an weeding mechanism of an automated mechanical intra-row weeder. The machine was developed to be combined with a machine vision system for detecting crop plant locations and controlling the weeding actuator motion to execute mechanical weeding operations without damaging crops. The rotating tine weeding mechanism was powered by a brushless dc (BLDC) motor. Two experiments were conducted to observe the effect of the mechanism on top-view weed canopy area and the power consumption of the rotary tine mechanism. The tines were tested at different working depths, tine shapes, forward travel speeds and rotational speeds. Significant differences were observed in weed canopy area across travel speeds ranging from 0.8 to 2.4 km/h and across working depths of 25.4 mm and 50.8 mm. Interaction of depth and travel speed also had an effect on weed canopy area. Rotation speeds had an effect on power consumption. In addition, reducing the number of tines from five to three resulted in a large reduction in power consumption.

Introduction

Weeds are a major problem in crop production generally, and in vegetable crops specifically. Weeds compete with crops to obtain moisture, sunlight and soil nutrients. This competitive nature will unfortunately affect the crop yield (Slaughter et al., 2008). To prevent serious yield losses from early season weed competition, Gianessi and Sankula (2003) reported that most crops require that the field be kept weed-free for four to six weeks after planting. Vegetable crop production is a major contributor to the US economy with a value of 11.2 billion dollars in 2010, an increase of three percent compared to 2009 (USDA, 2011). Thus lowering weed control cost in vegetable crops has potential to make a very large economic impact.

Weed infestations can be controlled though several different methods. Manual weeding, either using bare hands or hand-held hoes, is time consuming and laborious. Manual weeding of vegetable crops can require up to 158 hours of labor per hectare (Gianessi and Sankula, 2003), which means that many workers are required to perform weed control. Furthermore, the U.S. farm labor cost has increased from $0.10/hour in 1940s to $12/hour in 2010. However, this method is often used in organic production since this type of farming forbids use of any method that alters the synthetic chemical-free quality of its produce.

Many farmers switched from using manual weeding to chemical weeding. Herbicide spraying was introduced in the mid-20th century (Cloutier et al.,2007; Hakansson, 2003) and was demonstrated to be effective in controlling weeds. The cost of herbicide application was more economical than mechanical or manual weeding. It also helped to reduce yield loss, since mechanical cultivation has difficulties in being performed in a timely manner, due to wet fields making field entry difficult (Hakansson, 2003). However, renewed interest in mechanical cultivation has grown due to environmental concerns, the growing demand for pesticide-free produce, and also increasing herbicide resistance in weeds (Upadhyaya and Blackshaw, 2007). Herbicide application is also becoming more restricted with increasing pesticide use regulations, consumer concerns and a growing interest in organic foods (Slaughter et al., 2008).

Mechanical weeding or cultivation has a long history. Weeding tools pulled by draft animals were developed even before tractors were introduced. Mechanical weeders use three main techniques for either killing weeds or slowing their growth: 1. burying weeds, 2. cutting weeds and 3. uprooting weeds. Burial of weeds is accomplished through the action of tillage tools (Gianessi and Sankula, 2003) and usually done during land preparation when soil conditions are enhanced through tillage. Cutting and uprooting weeds are performed by mechanical tearing and breakage of the weeds from the soil, and is usually done during cultivating tillage after crop planting (Cloutier et al., 2007). The majority of commercially-available mechanical weeders focus on controlling weeds between rows or in the inter-row area (Cloutier et al., 2007). There are only a few machines that can control weeds inside the crop row, or in the intra-row region.

Finger weeder, torsion weeder and brush weeder mechanisms have potential to be effective mechanical means for controlling intra-row weeds because they can target weeds as close as possible to the crop. A limitation, however, of finger weeders and torsion weeders is that they require very accurate steering to keep the mechanism close to the crop. Brush weeders also require positioning accuracy of the brushes, and an operator controls the vertically-rotated brushes in and out of the crop row and are able to not only uproot weeds, but also bury and cut weeds (Bowman, 1997; Cloutier et al., 2007; Weide et al., 2008; Melander, 1997; Fogelberg and Kritz, 1999; Kouwenhoven, 1997). Nylon brushes used by the brush weeder, however, can produce much dust, especially when the operation is done in under dry soil conditions. Flexible tines, instead of nylon brushes, can be used to prevent this problem.

The function of an operator to control the tines movement can be replaced with an automation system. Automation offers the possibility to determine and differentiate crop from weeds, and at the same time, remove the weeds with a precisely controlled device. Automated weeders developed by Tillett et al. (2008), Astrand and Baerveldt (2002), Cloutier et al. (2007) and Griepentrog et al. (2006) provide example of how automatic control of mechanical weeding has good potential.

For automated weeders, there are no reports on the use of an electrical powered weeding mechanism. This research focuses on this issue. The overall goal of this research was to investigate the design and performance of a rotating tine mechanism intended for automated intra-row mechanical weeding in vegetable crop production. This mechanism consisted of a horizontally-oriented disc with tines mounted on it powered with a brushless DC (BLDC) motor. This system was attached to an automated intra-row weeder chassis. Expected weed control efficacy was accessed through measurements of top-projected weed canopy area using image analysis. The specific objectives of this work were to (1) investigate the effect of operational parameters such as working depth, travel speed, rotational speed and number of tines on weed canopy area reduction, and (2) study the effect of machine settings on weeding mechanism power consumption.

Material and Methods

Two experiments were conducted at the Agricultural Engineering ISU Research Farm, Ames, Iowa using the rotary tine mechanism. Both experiments were carried out in Clarion soil (loam texture 42% sand, 37% silt and 21% clay) at a depth of 0 to 178 mm (USDA-NRCS, 2011).

The first experiment was conducted on November 10th, 2010 to investigate the weed control efficacy through measurements of top-projected weed canopy area using image analysis at different working depths, different rotation speeds and different travel speeds. In this experiment, five circular tines, with each tine having a diameter of 7.3 mm, were mounted on the rotating tine mechanism. The power consumption of the system was investigated by measuring the voltage and current consumed by the motor powering the mechanism. The experiment was treated as a split plot experiment in a 213 m long and 9.14 m wide plot that was sown with four strips of 0.762 m) width of annual ryegrass one month before the experiments. A three factor factorial design was used, with three tine mechanism rotational speed levels, three travel speed levels and two working depth levels (Table 4.1). There were two levels for working depth, 25.4 mm and 50.8 mm; three levels for travel speed, 0.8 km/h, 1.6 km/h and 2.4 km/h; and three levels for rotation speed, 175 rpm, 250 rpm and 400 rpm. The soil condition was hard and crusted, with and the rainfall for the previous month was 19.3 mm (Department of Transportation (DOT) weather station, Ames, Iowa).

Table 4.1: Levels of different travel speeds, different rotational speeds and different working depths used for the 1st experiment.

Factor	First Level	Second Level	Third Level
Working Depth	25.4 mm	50.8 mm	
Travel Speed	0.8 km/h	1.6 km/h	2.4 km/h
Mechanism Rotational Speed	175 rpm	250 rpm	400 rpm

A second experiment was conducted on September 30th, 2011 to observe the effect of the rotary tine mechanism on weed control efficacy through measurements of top-view weed canopy area using image analysis using two different tine blade shapes. In this experiment, only three tines were mounted on the rotating tine mechanism. The cross section shape of one set of tines were circular with a diameter of 7.3 mm. The other set of tines, called “sharp” were modified from the round tines by grinding the edges until they were shaped into a triangular-type of shape (Fig. 4.1). The voltage and current consumed by the system was measured and power consumption was calculated and compared using these two different tines. A 15.2 m long by 10.4 m wide plot was prepared. The experiment was conducted three weeks after annual ryegrass was sown. Inside the plot, there was a mixture of annual ryegrass and broadleaf weeds, but the majority of the weeds were broadleaves. The experiment was treated as a split plot experiment with three factors: two tine shapes, round and sharp; three travel speeds, 0.8 km/h, 1.6 km/h and 2.4 km/h; and three rotational speeds, 350 rpm, 450 rpm and 536 rpm (Table 4.2). The experiment consisted of six strips, each 15.2 m long. Buffer zones were created inside the plot to ensure that the tractor forward speed was constant before applying the treatment factors. The working depth was set to 25.4 mm throughout the experiment. The soil condition was hard and crusted, and the precipitation for that month was 18.3 mm (DOT weather station, Ames, Iowa).

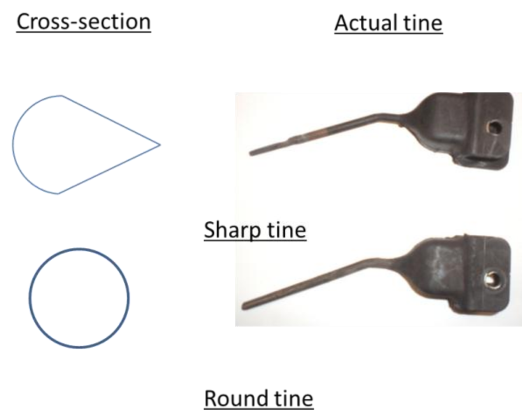

Figure 4.1: Two different tine shapes used in the 2nd experiment.

Table 4.2: Levels of different travel speeds, different rotational speeds and different working depths used for the 2nd experiment.

Tine shape	Round	Sharp	
Travel Speed	0.8 km/h	1.6 km/h	2.4 km/h
Mechanism Rotational Speed	350 rpm	450 rpm	536 rpm

Weeding Equipment: Machine weed control was done using the rotating tine mechanism attached a custom-fabricated implement chassis towed by a 37.3 kW 2WD tractor (Model 2600, Ford, Detroit, Michigan; Fig.4.2). The different travel speeds were controlled by the tractor driver who adjusted the tractor's throttle setting while using the lowest gear available. The weeding mechanism was controlled using a laptop that communicated with an on-board controller and a data acquisition system attached to the implement using a wireless network router. The controller consisted of an industrial PC with a Pentium III processor, a speed controller to control the speed of the weeding mechanism motor and a wheel decoder that estimated the travel distance. A 48 V brushless DC (BLDC) motor (BLY344S, Anaheim Automation, Anaheim, Ca.) was used to control the rotational speed of the tine weeder. This motor was connected to a speed controller (MDC151-050601, Anaheim Automation, Anaheim, Ca.) which communicated with the PC via a custom-built interface board. Three 12 VDC deep-cycle batteries were used to operate the BLDC motor. The power supply for the whole system was located underneath the data acquisition system using four 12 VDC deep cycle batteries, three batteries for the tine weeder motor and 1 battery for the computer. It was estimated that battery-based power supply had capacity to operate the system for 4-6 hours.

A graphical user interface (GUI) program was developed using C++ language via Microsoft Visual Studio to control the tine mechanism motor and to acquire measurements of the motor's current, motor's voltage usage and actual motor rotational speed. A special program was developed to change the cutter rotation speeds at specific travel distances. The working depths of the tine mechanism were adjusted manually. The BLDC motor's rotational speed was controlled wirelessly using a laptop and a wireless router that was connected to the onboard computer. Once the rotating tine mechanism's cart wheel moved, the wheel decoder provided the distance travelled. When the mechanism started moving and was engaged with the soil, the actual rotational speed, voltage and current was measured and logged (Fig. 4.3).

Figure 4.2: Rotating tine mechanism consisted of a disc with tines mounted on it. The mechanism is driven by a BLDC motor using a chain drive system.

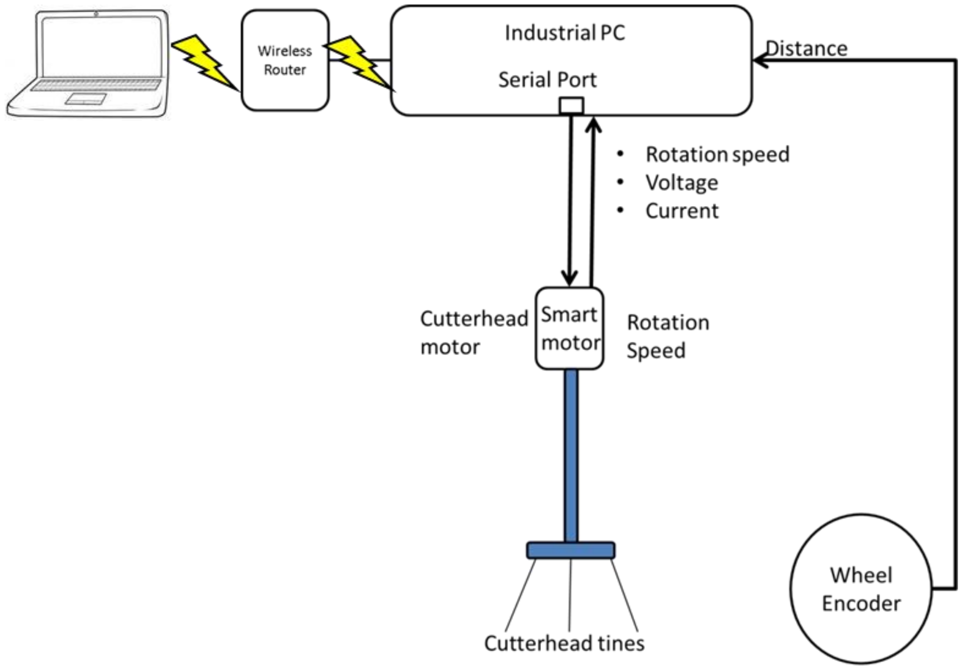

Figure 4.3: Block diagram of the rotating tine mechanism control and data acquisition system.

Image Acquisition: The plot was measured to indicate start and end points using flags. The location where different treatments were applied were marked using flags after measuring with a wheel encoder that was attached to the right rear wheel of the weeder. This procedure was used to identify when and where to initiate changes in rotational speeds and also to guide image acquisition for each treatment.

In this research, image pixels classified as containing vegetation were assumed to represent weed canopy area. For the first experiment, images of weeds were acquired using a Sony CCD camera (HDR-HC5, Sony, Japan) with a two Megapixel spatial resolution. A 25.4 x 25.4 cm square quadrat frame was used. For the second experiment, images of the weed coverage were taken using a Digital SLR camera (EOS Rebel T2, Canon, New York, NY) with a 55 mm lens and a 4 Megapixel spatial resolution. A 15.2 x 15.2 cm square quadrat frame was used as a reference to calculate the weed canopy area. The images were acquired directly over the quadrat frame at a height of 1.78 m from the ground. Three images per treatment were captured. Images were taken before machine weeding and after machine weeding. The location of each image before machine weeding was marked using sticks, to ensure that the same location was imaged after machine weeding. This procedure was done so that good quantitative observations could be made on the effect of mechanical weeding. For images after machine weeding, the area inside the quadrat frame was cleaned manually. The cleaning process had to be done very carefully as to clear out only the weeds that were uprooted by the machine. Images were then processed using custom-developed software using Matlab script to calculate the top-projected weed canopy area through image analysis.

Image Processing: Images captured during the experiment were processed using a commercial image processing software (Image Processing Toolbox version 1.4, Matlab, Natick, MA). The images were decomposed to red, green and blue layers. The green channel was used for segmentation because the images contained weeds with green color. A region of interest (ROI) was determined by selecting the whole area inside the quadrat frame. The image histogram was calculated, and a threshold was chosen manually based on the image histogram, choosing the value that separates two curves, where one represented the weed pixels and the other one represented the background pixels. A binary image was produced based on the histogram threshold (Fig. 4). In the first experiment, no morphological processes were used. However, in the second experiment, morphological processes of opening and thinning were used to clean the segmented images. In both experiments, weed pixel reduction, WC, was calculated using the equation,

$$\text{WC}(\%) = ((P_c - P_G)/P_G) * 100 \quad (1)$$

where

P_c is the number of pixels inside ROI with value '1' for area without weeding (control) and

P_G is the number of pixels inside ROI with value '1' for area after weed control .

Statistical analysis: In the first experiment, two strips were treated with the main plot treatment, the working depth. Each working depth strip was treated with three replicates of all levels of travel speeds. Within each replicate, all levels of rotation speeds were applied. The SAS (SAS Institute, Cary, N.C.) MIXED procedure was used to analyze separately two response variables, weed pixel reduction and power consumption, with working depth treated as a fixed effect in the main plot, and the interaction between depth and replicates (strips) of working depth as the random effect in the main plot. Travel speed, replicates of travel speed, rotation speed, interactions between travel speed and rotation speed, interactions between depth and rotation speed, interactions between travel speed and depth and the 3-way interaction between depth, travel speed and rotational speed were treated as fixed effects in the split plot level. All other interaction between tine, travel speed and rotational speed were treated as split plot random effects. For fixed effects where significance was detected, least square means was used to compare response variables across levels.

For the second experiment, each three strips were treated with the main plot treatment, tine shape. Each strip for each tine shape was treated with different levels of travel speeds. Within each strip, all levels of rotation speeds were applied. The SAS (SAS Institute, Cary, NC) MIXED procedure was used to analyze separately two response variable, reduction in weed canopy area and power consumption, with tine shape, travel speed and interaction between tine and travel speed treated as fixed effects. The interaction of tine shape and rotational speed was treated as a random effect. For fixed effects where significance was detected, the least square means was used to compare across levels.

Results and Discussions

This section is divided into two sections, weed pixel reduction and power consumption. In each section, results from both experiments are shown and explained.

Weed pixel reduction: In the first experiment, there was some evidence that weed pixel reduction efficacy was affected by working depth ($F_{1,2}$=10.04; P= 0.0869). There was also strong evidence of significant travel speed effects ($F_{2,86}$=20.8; $P < 0.0001$). Using least square means, the slowest travel speed of 0.8 km/h had an average reduction in weed canopy area of 58.2% with standard error of 2.7% compared with the medium travel speed of 1.6 km/h with an average reduction in weed canopy area of 52.6% with standard error of 2.7%. The fastest travel speed of 2.4 km/h had an average reduction in weed canopy area of 42.4% with standard error of 2.7%. There was no statistical evidence of an effect across rotational speeds ($F_{2,86}$=0.09;P=0.9136), nor was there statistical evidence of an interaction between working depth and travel speed ($F_{2,86}$=2.04; P=0.1369). There were also no statistical evidence of an interaction of travel speed and rotational speed ($F_{4,86}$=0.64;P=0.6383).

Figure 4.4: Left image shows the machine weeding inside a quadrat frame. Right image shows the processed image used for calculating weed pixel reduction.

The weed pixel reduction for 25.4 mm working depth across travel speed and rotational speed showed mixed patterns (Fig. 4.5). However, the weed pixel reduction decreased when the travel speed was increased. This was expected because when the tractor goes faster, the tines would make paths through the soil per area with a fixed rotational speed. For rotational speeds, the weed pixel reduction was almost similar when the slowest travel speed was used. The fastest travel speed showed an increase in weed pixel reduction when the rotational speed was also increased. Overall, the working depth of 25.4 mm produced weed pixel reduction estimate of 44% with a standard error of 3.3%.

The weed pixel reduction for a 50.8 cm working tine depth across travel speed and rotational speed showed significant patterns (Fig.4.6). Similar to the previous working depth, the weed pixel reduction decreased when the travel speed was increased. Across rotational speeds, the weed pixel reduction decreased when rotational speed was increased. This was not expected, because with the same travel speeds, the weed pixel reduction should increase because of the increase in rotational speeds which causes the tines to work at the same path longer, causing better soil and weed disturbance. Because the operating depth was increased, the BLDC motor probably had to increase the current drawn into the system to increase or to maintain the rotational speed. As a result, the intended rotational speed could not be achieved. This could have caused the power consumption of the system to rise, which will be discussed in the next section. The weed pixel reduction estimate for this working depth was 58%, with a standard error of 3.3%. This estimate is higher than the previous working depth, which was expected as the deeper the weeding was performed, the more weeds could be destroyed.

With the slowest travel speed, the tine weeding mechanism should be able to produce good weed control effect with increasing rotational speed. The results variations were mainly due to the plot layout which was too long for different working depths. Using a long distance resulted in variation in the results mainly due to soil and weed density variation.

The rotational speeds of R1 (slow), R2 (medium) and R3 (high) were different when working in different working depths. This occurred because the load was always changing due to the tines engagement with the soil and the BLDC motor used could not generate the proper torque to rotate at the desired rotational speed. A statistical analysis to test for difference showed strong evidence that there were differences in speeds for 25.4 mm working depth ($p<0.0001$) and 50.8 working depth ($p=0.0317$). When using working depth of 25.4 mm, the mean actual speed level for R1 was 176 rpm with a standard deviation of 36 rpm, mean R2 speed was 272 rpm with a standard deviation of 32 rpm and mean R3 speed was 329 rpm with a standard deviation of 26 rpm (Fig. 4.7). Working depth of 50.8 mm showed lower actual rotation speeds compared to the previous depth (Fig. 4.8). Actual mean speed for R1 was 163 rpm with a standard deviation of 63 rpm, mean R2 speed was 214 rpm with a standard deviation of 52 rpm and mean R3 speed was 247 rpm with a standard deviation of 66 rpm.

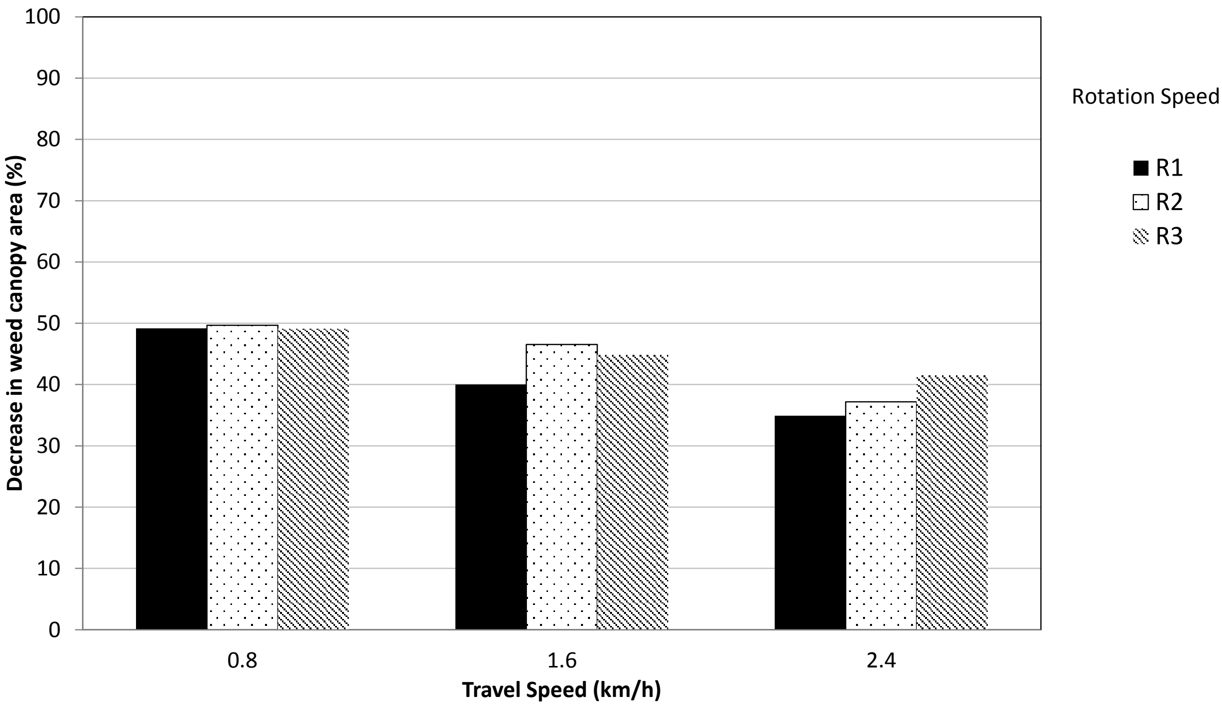

Figure 4.5: Decrease in weed canopy area with different travel speeds and rotational speeds for 25.4 mm depth. R1 indicates the slowest rotational speed and R3 indicates the fastest. Weed pixel reduction decreased when travel speed was increased.

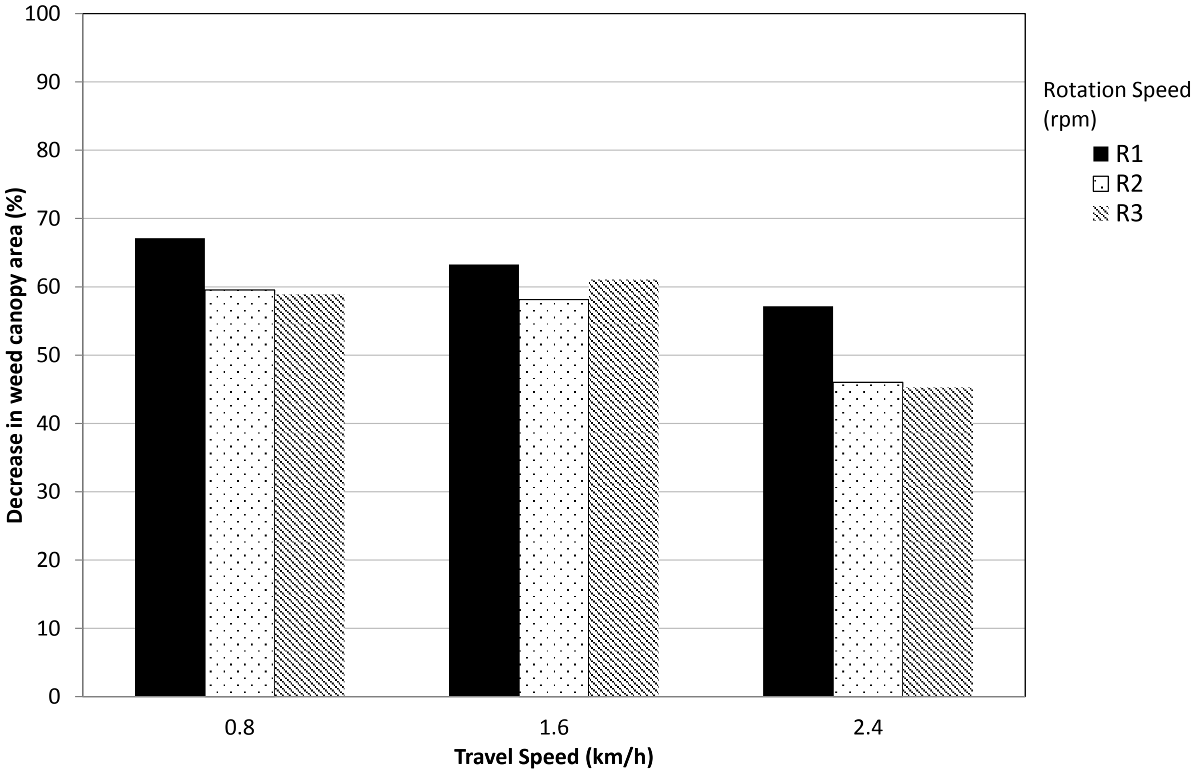

Figure 4.6: Decrease in weed canopy area with different travel speeds and rotational speeds for 50.8 mm. R1 indicates the slowest rotation speed and R3 indicates the fastest. Weed pixel reduction decreased when travel speed increased.

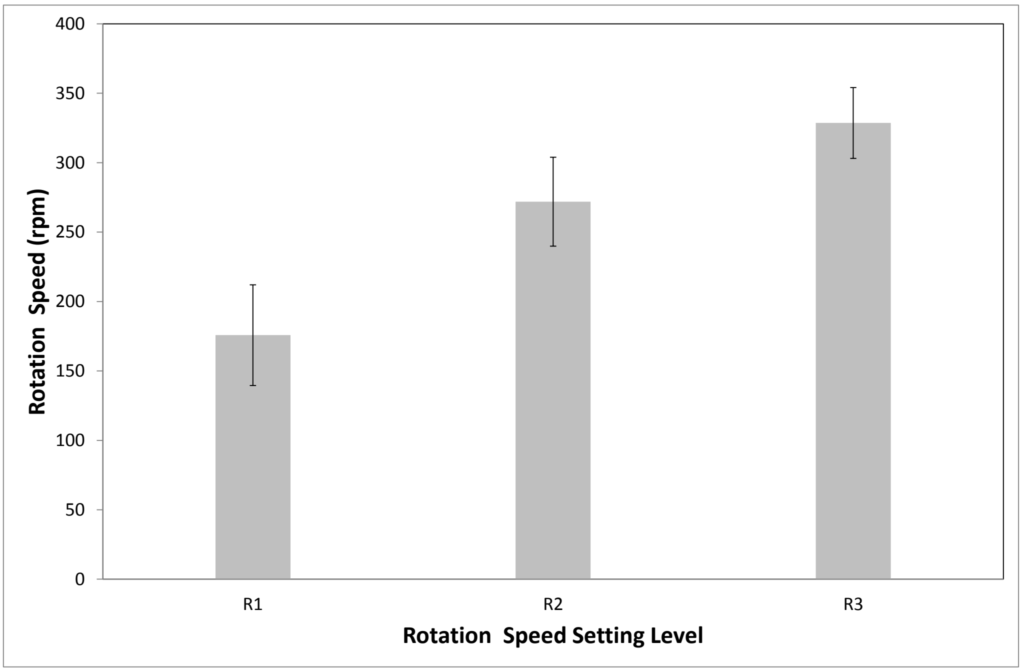

Figure 4.7: Average rotation speed levels at 25.4 mm working depth with standard deviation. Statistical analysis showed that there were differences in the speed levels (p < 0.0001).

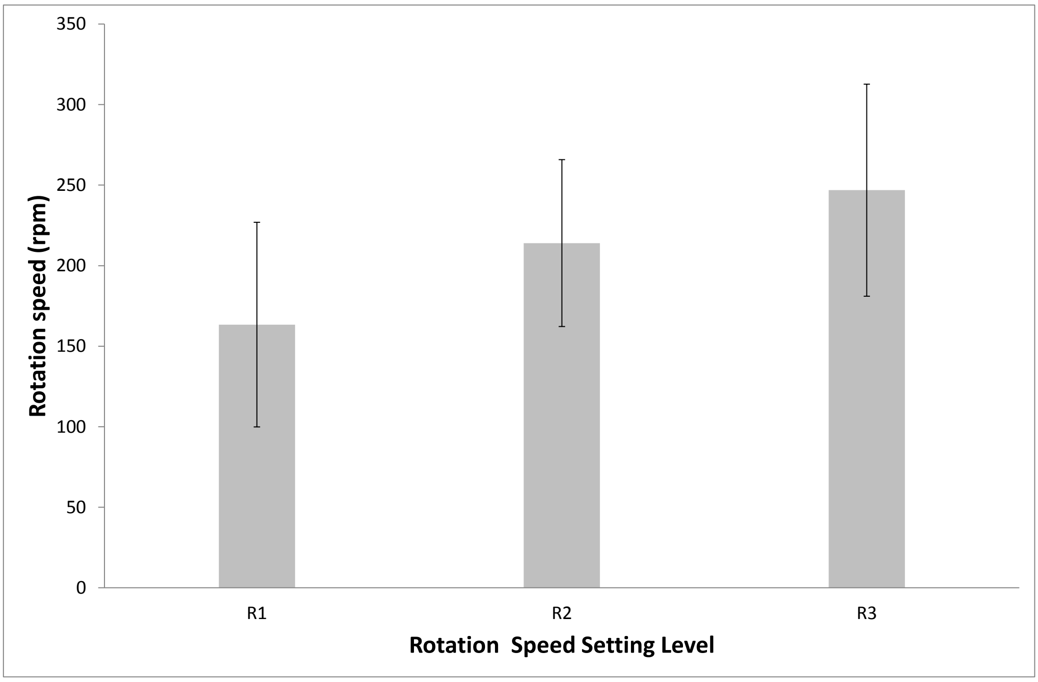

Figure 4.8: Average rotation speed levels at 25.4 mm working depth with standard deviation. Statistical analysis showed that there was difference in the speed levels (p=0.0317).

In the second experiment, there was no evidence of differences in weed pixel reduction across different tine shapes ($F_{1,12} = 0.29$; P = 0.598), but there was evidence of differences in weed pixel reduction across travel speeds ($F_{2,12}$ =8.09; P = 0.006). There was evidence of interaction between tine shape and travel speed ($F_{2,12}$ =4.62;P=0.0324). Using the least squared differences, significant differences between tine and travel speed were identified (Table 3).

Table 4.3. Comparison of mean weed pixel reduction across different tines and travel speed.

Tine	Travel Speed		
	0.8 km/h	1.6 km/h	2.4 km/h
Round	78.3%	62%	50%
Sharp	65.5%	57.5%	62.1%

For the round tine weeding mechanism, when the travel speeds increase, weed pixel reduction decreases (Fig. 4.9). This implies that the most effective weed control should occur when the lowest travel speed was used. However, from the lowest travel speed, the highest weed pixel reduction was achieved using the middle rotational speed, 450 rpm. This might have been caused by several issues such as better soil conditions in the middle of the plot resulting in a more effective weed control. The lowest weed pixel reduction was obtained with the fastest travel speed and the slowest rotational speed, a result which was anticipated.

Weed pixel reduction using sharp tines was variable (Fig. 4.10). When the rotational speed was at 350 rpm, the weed pixel reduction decreased when the travel speed increased. Similar results were obtained when the maximum rotational speed was used. However, when the rotational speed was at 450 rpm, there was an increase in weed pixel reduction when the speed reached 2.4 km/h. This was unexpected because simulation results showed that low weed pixel reduction should be obtained when using the middle rotational speed with the maximum travel speed. This result might have been caused by errors in image acquisition when the same actual location should be taken before and after machine weed control. The weed density in that particular area might have low weed density that could have affected the results as well. This was also probably because of the tine offset movement from its original location due to difficult soil conditions.

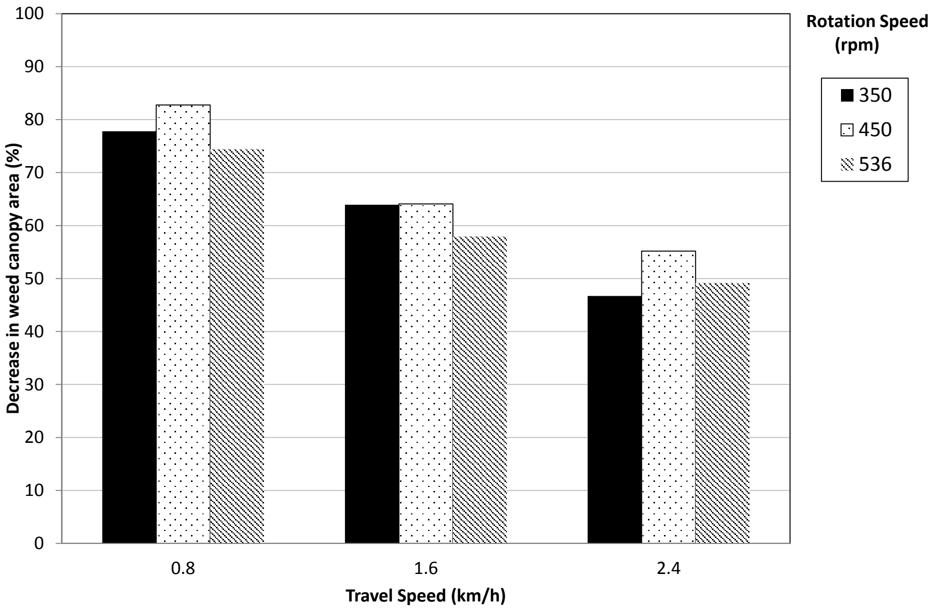

Figure 4.9: Decrease in weed canopy area with different travel speeds and rotational speeds using round tines. Weed pixel reduction decreased when travel speed increase.

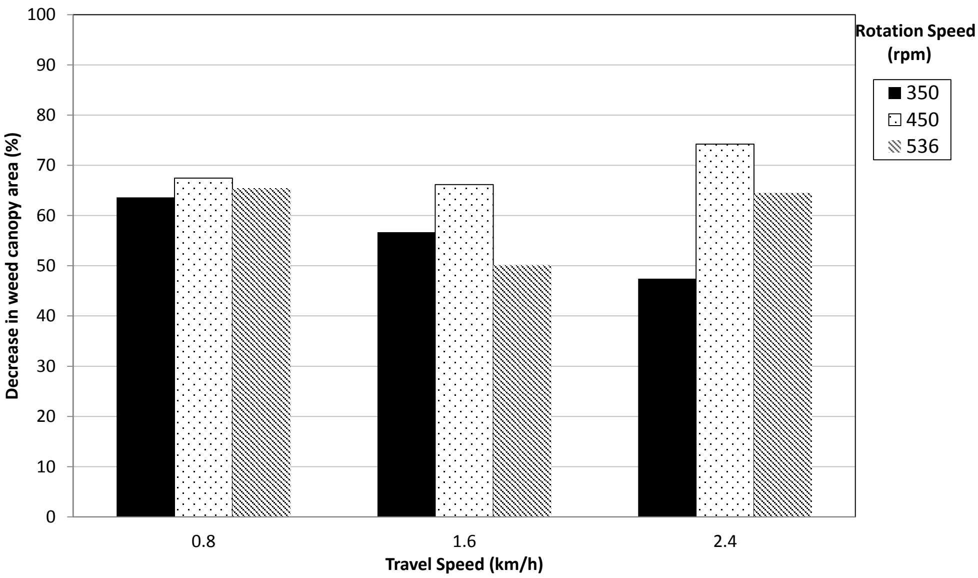

Figure 4.10: Decrease in weed canopy area with different travel speeds and rotational speeds using sharp tines. Weed pixel reduction decreases when travel speed increase.

Power Consumption: In the first experiment, there was no statistical evidence of a difference of power consumption across working depth ($F_{1,1} = 4.53$; $P = 0.2796$), travel speed ($F_{2,60} = 0.14$; $P = 0.8722$) or rotational speed ($F_{2,60} = 0.01$; $P = 0.995$). Although no statistical evidence of rotational speed effect, the power consumption across rotational speeds showed small increases as rotational speed increased (Fig. 4.11 and 12). The power consumption for different rotational speeds were anticipated because theoretically rotational speed is directly proportional to power consumption. The mean power consumption for 25.4 mm working depth was 378 W with a standard error of 54.7 W.

There were no significant visual evidence that there was an influence on power consumption by travel speeds and rotational speeds for 50.8 mm working depth (Fig. 4.12). The mean power consumption for 50.8 mm (2 in.) working depth was 576 W with a standard error of 75.8 W. The power consumption increased by 52% when the working depth increased from 25.4 mm to 50.8 mm.

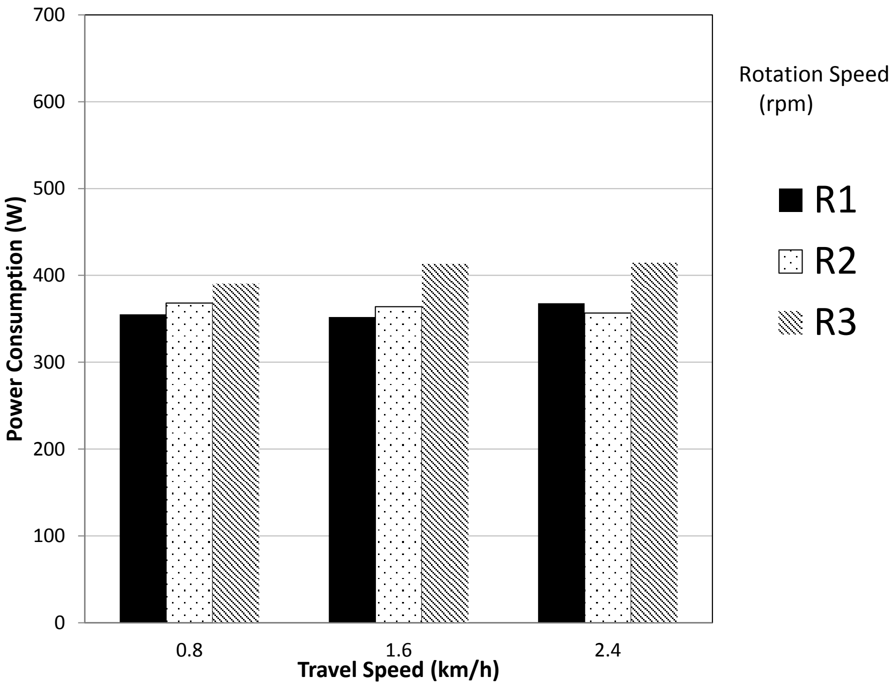

Figure 4.11: Power consumption during weeding with different travel speeds and rotational speeds for 25.4 mm. R1 indicates the slowest rotation speed and R3 indicates the fastest.

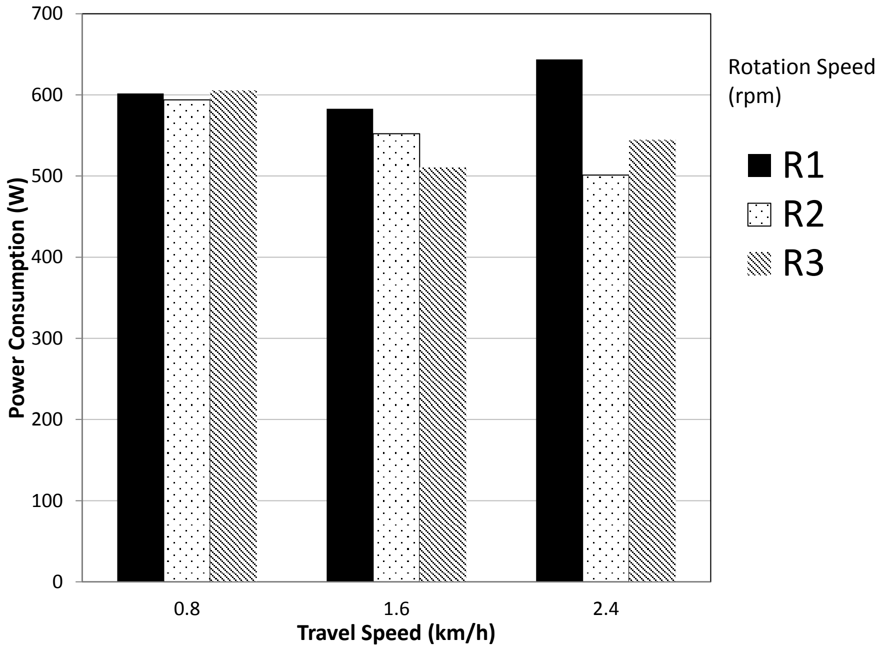

Figure 4.12: Power consumption during weeding with different travel speeds and rotational speeds for 50.8 mm. R1 indicates the slowest rotation speed and R3 indicates the fastest.

The results of the second experiment showed that there were no evidence of a tine shape effect ($F_{1,2}$ = 4.77; P = 0.16) or of a travel speed effect ($F_{2,1}$ = 0.00 ; P = 0.99) on power consumption. There was, however, evidence that there were differences in power consumption across rotational speeds ($F_{2,4}$ = 9.56; P = 0.03). The highest power consumption was observed when using the fastest rotation speed, 536 rpm, and was a mean of 182 W and a standard error of 9.4 W. The lowest rotation speed, 350 rpm, had the lowest power consumption with an estimate 123.5 W and standard error of 9.4 W.

The power consumption of the tine weeding mechanism during weed control at 25.4 mm working depth for the different sets of tines were plotted (Fig. 4.13 and 4.14). Overall, the power consumption was less than the rated power, 615 W of the tine weeding mechanism. The maximum power observed was slightly over 200 W, and this was observed when using round tines. The sharp tines resulted in power consumption below 200 W. The minimum power consumption was roughly 100 W for both sets of tines.

Even though the soil conditions were dry and hard, the power consumption was one-third of the actual rated power of the motor. However, some variability was obtained when different rotational speeds were used. This may have been caused by the variability in the soil conditions. The original tines set showed some increase in the power consumption when the travel speed was increased. The sharpened tines set showed variable results, the lowest and middle rotational speed settings showed decreases in power consumption while the maximum rotational speed showed an increase. This might be an indication that in the middle of the plot, the soil is softer compared to the other areas inside the plot.

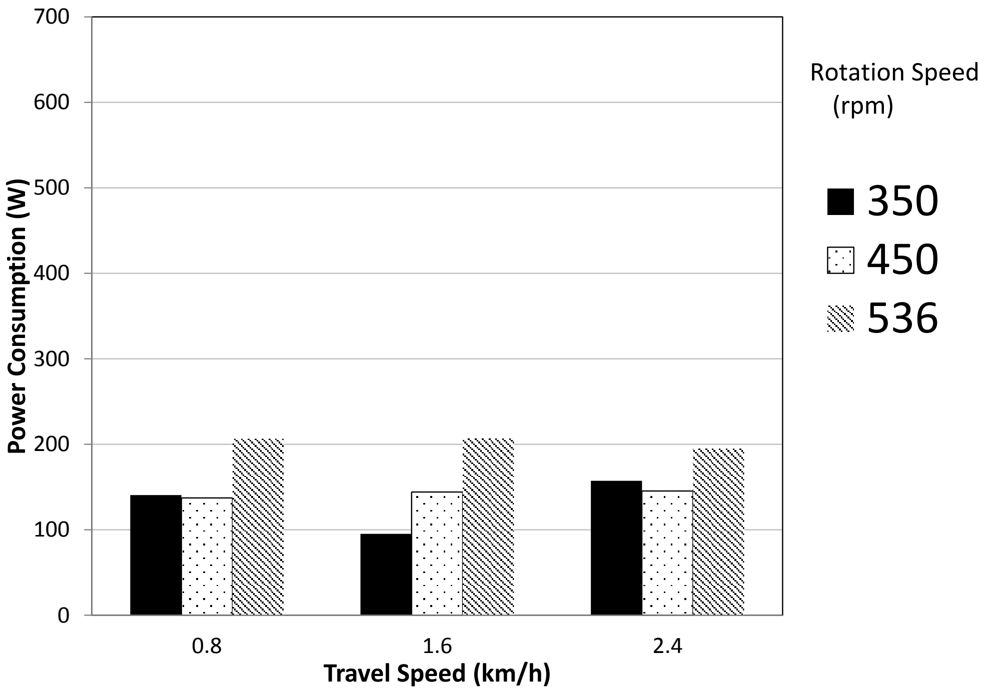

Figure 4.13: Power consumption during weeding with different travel speeds and rotational speeds using round tines.

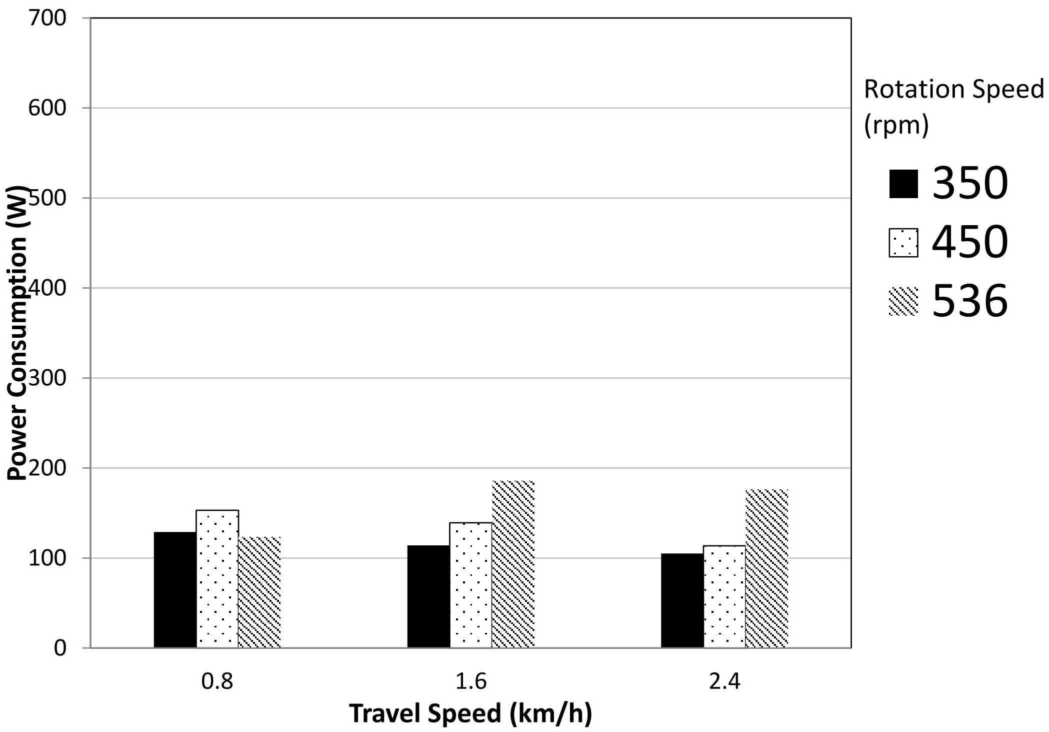

Figure 4.14: Power consumption during weeding with different travel speeds and rotational speeds using sharp tines.

Conclusion

A rotating tine weeding mechanism was developed for an automated intra-row weeder. From the two experiments conducted it can be concluded that:

- Tine depth and forward travel speed had an effect on weed canopy area reduction. There was statistical evidence that tine depth and travel speed had an effect on weed canopy area. Deeper working depth and a slow travel speed can achieve good weed control. Therefore, it is very important to consider these two factors to achieve good weed control effect.
- By reducing the number of tines from 5 to 3, power consumption of the system was reduced substantially. There was statistical evidence that rotation speed had an effect on power consumption when using 3 tines.

- The rotating tine mechanism has potential for low power weeding at slow travel speeds, which is well suited for autonomous intra-row weeding robots.

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CHAPTER 5. GENERAL CONCLUSIONS

This research achieved the main goal of developing a mechanical intra-row weed actuation system focusing on weed control intentionally for vegetables crops production. The prototype underwent several stages of development to achieve this goal. The final prototype used a pivot arm concept where an integrated servo motor was used to control the pivoting arm motion via a chain drive system. The chain drive system drives a rack and pinion mechanism to guide the swinging of the pivot arm. The weeding mechanism shaft was rotated using a chain drive system powered by a brushless dc motor.

The first objective was to study the weed control efficacy using different settings. A simulation was developed to investigate the effect of number of tines on the working zone at different travel speeds and different rotational speeds. This simulation was used as a basis to study the weed control efficacy. Using this simulation, minimum rotation speeds for specific travel speeds were obtained. The simulation also showed that with increasing travel speeds, the required rotational speed had to be increased to cover the same working zone. This result was also through two field experiments conducted using different versions of the prototype. In addition, the first experiment also showed that with increasing working depth, the weed canopy area reduction also increased. In the second experiment, two different sets of tines were used, round and sharp tines, and the number of tines were reduced from five to three. The rotational speed requirements increased because of this change, but there was no significant evidence that there were any difference using round and sharp tines.

The second objective was to study the power consumption used by the weed actuation system during operation. The power consumption was monitored during the field experiments and showed that power consumption was increased when the working depth was increased. The power consumption also increased across rotational speeds. There was also a large reduction in power consumption when number of tines was reduced from five to three. However, there were no noticeable patterns using round and sharp tines.

The third objective was to compare the weed control efficacy of manual weeding with machine weeding. Results from the first experiment showed that machine weed control efficacy was lower than manual weeding, where the mean was 44% with standard error of 3.3% for a 25.4 mm working depth and a mean value of 58% % with standard error of 3.3% for 50.8 mm working depth. Another field experiment conducted using the new weed actuation system was done but with some changes in the experiment. The working depth used throughout the experiment was 25.4 mm (1 in) and tested round and sharp tines using three levels of travel speed and two levels of rotation speeds. The results showed that there was no significance using different tines in terms of weed control efficacy. For round tines, the mean weed canopy area reduction was 64% with standard error of 5% and for sharp tines, the mean was 62% with standard error of 5%. Efforts must be continued in order for the weed actuation system to achieve the same weeding performance of manual weeding.

Suggestions for Future Work

This research together with the prototype developed has great potential to be expanded to create a working prototype that could be used for intra-row weeding for vegetable production. This prototype will be integrated with a vision system in the near future, thus opens a wide area of research to conduct.

Based on the experience gained from this research, there are several recommended future research topic:

1. Study the performance of the prototype in terms of the lateral speed of the pivot arm using different settings such as travel speeds and different rotational speeds.
2. Study the performance of the prototype after integrating with a vision system for weed-crop detection.
3. Study the performance of the prototype when using two weeding mechanisms that move opposite to one another.
4. Study on the most suitable tine design for achieving the best weed control efficacy.
5. Study the performance of the prototype with actual soil conditions used in vegetable farms.

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