A Conceptual Design and Economic Analysis of a Small Autonomous Harvester

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ABSTRACT

Current trends in agricultural equipment have led to an increasing degree of autonomy. As the state of the art progresses towards fully autonomous vehicles, it is important to consider assumptions implicit in the design of these vehicles. Current automation in harvesters have led to increased sensing and automation on current combines, but no published research examines the effect of machine size on the viability of the autonomous system. The question this thesis examines is: if a human is no longer required to operate an individual harvester, is it possible to build smaller equipment that is still economically viable?

This thesis examines the appropriateness of automating these machines by developing a conceptual model for smaller, fully autonomous harvesters. This model includes the basic mechanical subsystems, a conceptual software design, and an economic model of the total cost of ownership.

The result of this conceptual design and analysis is a greater understanding of the role of autonomy in harvest. By comparing machine size, machine function, and the costs to own and operate this equipment, design guidelines for future autonomous systems are better understood. It is possible to build an autonomous harvesting system that can compete with current technologies in both harvest speed and overall cost of ownership.

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Chapter 1. Introduction

In this chapter, the basic background of harvesting is established. Autonomy in harvesters is discussed, and the question of appropriate scale for autonomous harvesters is posed.

1.1 Background

Since 1910, the American agricultural workforce has declined by 10 million workers while the American population as a whole has increased by 216 million people(National Agricultural Statistics Service 2012a). American farmers have continued to produce more food for an ever-growing population with less and less labor. This is due in large part to the growing mechanization of agriculture, which has allowed one person to cultivate and harvest increasingly large tracts of land. The rise of mechanization, combined with the declining workforce and consolidation of farmland has led to larger farm equipment. An extreme example of this can be seen in a 48-row corn planter, which is 120 feet wide and can plant up to 100 acres per hour(John Deere 2013a). Devices like this maximize the individual output of one farmer, creating the ability to farm thousands of acres with limited hired labor.

Grain harvests have taken place since the Neolithic Revolution over 10,000 years ago. Grain harvest still follows the same basic steps that began at that time: reaping the plants, threshing the grain, and winnowing away the chaff. From the first farmers to the mechanization of agriculture during the industrial revolution, the process remained largely unchanged. Agricultural mechanization began with simple hand tools, and continued with animal and then steam powered threshing and grain separation. These parts of the harvest process were brought together in the first combines developed in the early 20th century(“Massey Ferguson Celebrates the 75th Anniversary of the MH-20 – the World ’ s First Self-propelled Combine Harvester” 2013). Since that time, combines have become larger and more refined, but still perform the same basic functions that were used to harvest grain 10,000 years ago.

In addition to increasing machinery size, agricultural equipment has become increasingly autonomous. Global Positioning System (GPS) navigation has enabled self-steering equipment, and equipment manufacturers are currently developing completely autonomous equipment. Farmers have integrated these technological advances into their equipment portfolio when it makes economic sense. Self-steering systems can pay for themselves by ensuring that row spacing is correct and eliminating overlap in the field by individually controlling planter boxes, allowing more rows to be planted and reducing wasted seed. Self-steering harvesters significantly reduce operator fatigue and allow operators to work longer hours, increasing productivity. Automation in row crops continues to develop, and will continue to be popular with farmers who can pay for the technology with the productivity it provides.

1.2 Problem Statement

As technology continues to develop towards more and more autonomous equipment, it is important to note that little development is being done outside of traditional equipment designs. Everything being developed for use in commodity agriculture exists as a retrofit or extension of current agricultural equipment design, such as GPS based yield monitoring and autosteer technologies. However, transitioning from autonomy that augments the human operator to a fully autonomous system provides an opportunity to completely reexamine the design of modern agricultural equipment. Without a human operator, is it possible to build smaller, more cost effective agricultural equipment? When developing new technology, engineers are frequently concerned with questions of “can it be built?” However, an important question in to consider in the early stages of this current era of machine automation is “should it be built?” The goal of this thesis to present a method for evaluating machine design that considers the total cost of ownership. To demonstrate this, a small scale harvester will be compared against a conventional combine and a full sized autonomous combine.

In order to reach a conclusion, many aspects of agricultural equipment design will be explored. The mechanical design of a smaller, fully autonomous system will be proposed and compared to existing methods. The goal of the proposed system is to reduce cost to the farmer. More importantly, the economic feasibility and impact of this proposed system will be evaluated and discussed. The history of farm equipment is littered with “labor saving” devices, but farmers are reluctant to adopt new technology without sound economic reasoning. Exploring the economic foundations behind equipment decisions will help provide requirements and guidelines for equipment design.

In addition to reducing costs, one goal of the proposed system is to reduce the risk absorbed by the farmer. In the current system, farmers bear an extraordinary share of the economic risk of production relative to their reward. Little has changed since President John F. Kennedy proclaimed, “For the farmer, is the only man in our economy who has to buy everything he buys at retail - sell everything he sells at wholesale - and pay the freight both ways(Kennedy 1960).” Purchasing a combine is an expensive proposition, and the proposed harvester will provide a much cheaper alternative for small farms.

One issue in doing both engineering and economic analysis is scope. When calculating efficiency or doing economic analysis, an appropriate level of detail needs to be established in order to avoid becoming mired in details that are not significant for the overall analysis. For this thesis, the design of machinery stops at the farm gate. Automation will one day be far more pervasive, with autonomous tractor-trailers hauling grain, automated weighing systems replacing the hand-written weight tickets at grain elevators, and autonomous shipping systems moving barges of grain down the Mississippi River. The designs discussed here, though, are intended for harvesting in the fields. This is not a simple task as several systems have to work together to in order to effectively move the grain from the stalk to the truck or to the grain cart hauling it away, but the analysis is limited to the reaping, threshing, and grain separation systems that make up the foundation of harvesting systems. This allows for consistent comparisons of the cost of each method, and the economic analysis of each method closely mimics the comparisons that would be made by a farmer.

Modern combines can harvest a wide variety of crops, including small grains like wheat, rye, barley, and oats as well as more exotic crops such as milo, canola, mustard, and peas. However, the calculations presented in thesis are limited to corn production. Corn is the most popular crop in America, both in acres planted(Environmental Protection Agency 2013) and cash value of the crop(National Corn Growers Association 2013). In order for a commercial harvester for general use to be successful, it must perform well when harvesting corn. Corn has higher harvesting power requirements than other grains, making the power requirements for corn an important benchmark in harvester design. Corn's ubiquity and high power requirements make it an ideal benchmark for the evaluation of the proposed system. The harvest calculations used for corn are also valid for other small grains, and the economics of harvest remain largely the same, with slight variations in power, fuel requirements, and harvest speed.

The scope of the economic analysis is limited to the major costs and benefits of the proposed system. Ownership costs including purchase costs, housing and maintenance facility costs, depreciation, and interest form the fixed costs for both the proposed autonomous system and the conventional method. Operating costs such as repairs, fuel, and labor all factor in to the variable cost, which varies with the hours each machine is used. Other costs such as transportation of the harvester to and from fields will also be considered. Comparisons to existing equipment will include a comparison of efficiency, specifically field efficiency, which measures the amount of work performed while the equipment is in the field. Also included in the economic analysis is the effect of smaller machines on land ownership. Current state of the art equipment is very large, and, for farms away from the grain belt, cost for new machines is prohibitively high. Smaller machinery is less expensive, therefore more accessible for smaller farmers. Not considered in the economic analysis are costs outside of those directly related to the harvester, such as moving grain from the field or the cost of operating a grain cart.

Chapter 1 of this thesis provided brief background data on the history of grain harvesting. It posed the question of appropriate scale for autonomous harvesters. It also outlined several of the issues facing modern farmers that the proposed harvest system will address.

Chapter 2 details published literature in the field, both on the economics of farm machinery and on the science of harvest machinery. A brief overview of the operation of a combine and the power required for harvest is given. A review of available product literature from current harvest equipment manufacturers is also discussed.

Chapter 3 discusses the history and current state of corn harvest to provide background information on harvester requirements. It provides the basic details of corn physiology and harvest metrics. The state of the art in harvest machinery is presented, as well as an overview of the current state of harvest and machinery automation. It also provides details on the infrastructure surrounding harvest that process the grain after it is removed from the field.

Chapter 4 provides the framework for economic analysis. A brief discussion of the basics of farm enterprise economics is followed by a detailed comparison of the proposed autonomous method, the current method, and an autonomous harvester of conventional size. The economic discussion will cover both the fixed cost and variable cost, and detail their calculations and the assumptions built into the discussion.

Chapter 5 discusses the conceptual design of the proposed system. It provides a high-level discussion of the methods used, the automation equipment needed, and power requirements of the conceptual design.

Chapter 6 is a comparison of the functional abilities of the proposed system and conventional systems. The abilities of each system will be compared for different field shapes, and the economics of each system will be examined in a custom harvesting scenario. The efficiency, speed, manpower requirements, and safety of the two systems will also be compared.

Chapter 7 will provide conclusions from the analysis presented in the thesis, as well as discussing future work and possible improvements.

Chapter 2. Literature Review

This chapter presents the current state of academic research regarding harvest technology, farm enterprise economics, and harvest automation. It also presents information on state-of-the-art harvest technology, as developed and built by equipment manufacturers.

2.1 Harvester Research

A great deal of academic research has been published concerning the function of combine harvesters. The basic design, encompassing the snapping rollers, headers, feeder housing, threshing cylinders, straw walkers, sieves, chaffers, and grain handling, is covered in detail in several textbooks(Hunt 2001; Stout et al. 1999; Uhl and Lamp 1966; Gregory 1988), and a typical combine layout is shown below in Figure 1.

Harvesting begins at the cutting platform, which performs the reaping of the crop. When harvesting small grains such as wheat and barley, a reel and cutter bar is used to gather the crop, as shown in Figure 1. Harvesting corn requires a different head using snapping rollers, which are discussed in greater detail in Section 3.4. After the crop has been reaped, it is then sent to the threshing unit, consisting of a cylinder that forces the crop against a “concave,” which is a metal screen or grate that removes the grain from the straw or cob. After passing through the thresher, the separating process begins. This process separates the grain out of the remaining crop material using shaking in straw walker or centrifugal force in a rotary separating system. The grain then progresses to the cleaning system, where a fan blows any remaining crop material out of the combine while the heavier grain falls through sieves and is collected into a bulk tank(Stout et al. 1999).

The configuration and layout shown in Figure 1, harvesting small grains such as wheat and barley with a tangential threshing unit and straw walkers, is very well researched. These technologies were state-of-the-art in the 50’s and 60’s when much of the initial research was occurring.

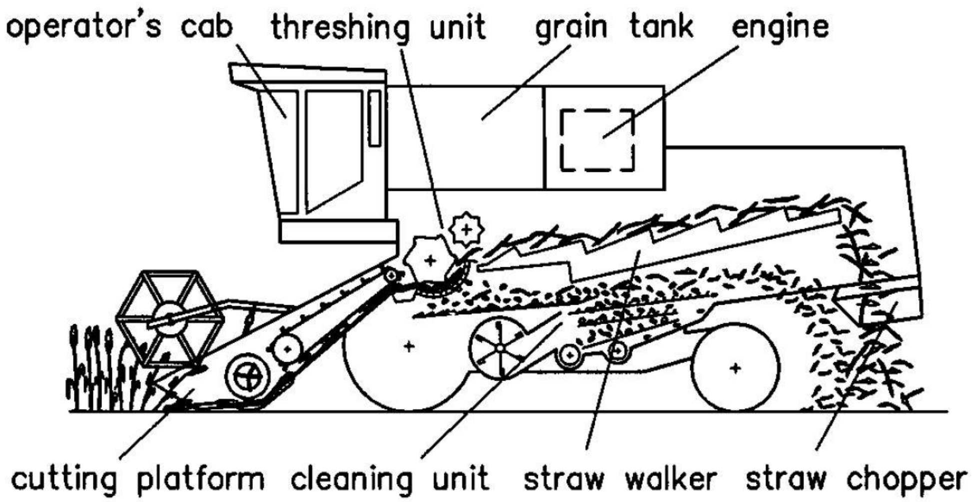


Figure 1: Basic combine design(Stout et al. 1999)

Modern combines utilizing axial threshing enjoy a much smaller base of published knowledge. Many of these technologies were developed and researched inside of large companies, and the data on their operation and performance characteristics are proprietary. While much of the research performed on these technologies remain proprietary information, some studies do exist. Power requirements have been modeled and tested for axial threshing in wheat and barley(Miu and Fellow 2001). In these tests, there was little power variations across a wide range of cylinder speed, but power requirements increase significantly when handling more crop material, as shown in Figure 2. Moisture levels, concave settings, and a variety of other factors also contribute to changes in power requirements, but material-other-than-grain (MOG) feed rate has the greatest effect.

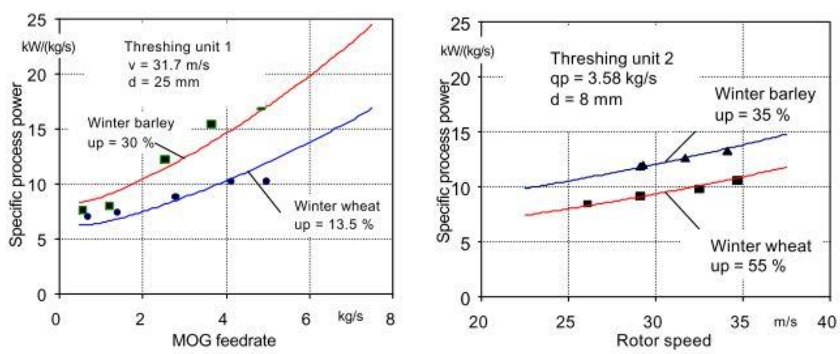


Figure 2: Effect of MOG Feed rate and Rotor Speed on Power Requirements(Miu and Fellow 2001)

Field efficiency is a widely researched area in agricultural machinery. Field efficiency is the ratio of time spent doing useful work in a field to the total time spent in the field. Typical values for field efficiency range between 65 and 80 percent for combines(American Society of

Agricultural and Biological Engineers 2011). Current research in field efficiency focuses on improving the calculation of field efficiency using GPS data(R. D. Grisso, Jasa, and Rolofson 2002), and using automation to improve field efficiency and operating time(Sørensen, Bak, and Jørgensen 2004)(Oksanen and Visala 2009).

Improving agricultural path planning algorithms involves deconstructing fields into discrete areas and then performing optimization algorithms to minimize time and distance needed to cover the field. These solutions often look nothing like the farmer's solution to path planning, but maximize the time spent harvesting and minimize turns. An example of one solved field path problem is shown in Figure 3.

Figure 3: Computer generated solution to field path planning(Sørensen, Bak, and Jørgensen 2004)

Many state extension services and land grant universities have researched harvester operation and performance. Colorado State University, Iowa State University, and Virginia Polytechnic Institute and State University have all published information regarding farm equipment effectiveness, performance, and economics. William Edwards has published several worksheets that calculate the costs associated with machine ownership. In addition to the standard expenses that comprise the fixed and variable costs, agricultural machinery can incur timeliness costs such as yield loss due to late plantings. Increasing machinery size increases ownership costs, but decreases operating and timeliness costs, as seen in Figure 4(Edwards 1989).

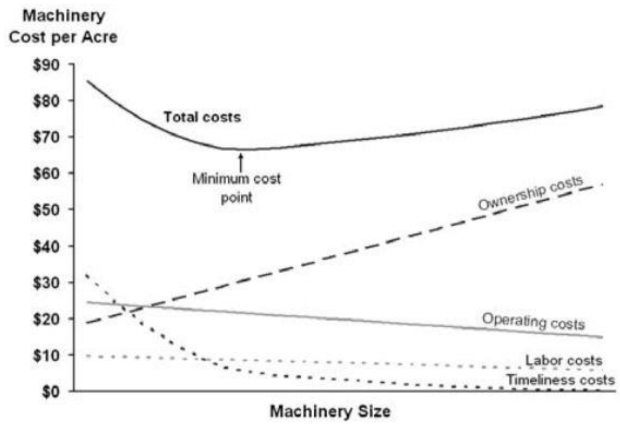


Figure 4: Machinery Size vs. Cost per Acre(Edwards 1989)

The Iowa State University Extension service provides worksheets to compare machinery ownership and custom hire costs. Several factors are included in the return on investment of owning a combine, including harvesting multiple crops and custom work for friends and neighbors. This worksheet provides insight in the calculations needed to compare methods of harvesting by evaluating usage against the costs associated with ownership(Iowa State University Extension Service 2009).

2.2 Product Literature

Conventional harvesters are a mature technology, with a large market throughout the world. In 2012, 9,898 combines were sold in the United States(Association of Equipment Manufacturers 2013). Major manufacturers of harvest equipment include John Deere, Case IH, New Holland, Gleaner, and Claas. By examining the product literature provided by the companies, an understanding of current state-of-the-art and harvest systems in general can be developed.

Conventional harvesters provide rough benchmarks for the proposed system, as well as various design alternatives. Some combines, such as the New Holland TC5070 shown in Figure 5, still use tangential threshing cylinder arrangements, though most have generally been replaced by axial threshing.

Figure 5: New Holland TC5070(“Farmsystems.sk” 2013)

The John Deere S690 shown in Figure 6 shows the more typical axial threshing and separating arrangement. This particular combine has 614 horsepower engine; a 30-inch diameter, 123-inch long, variable speed driven threshing rotor; 400-bushel grain tank; and weighs 44,541 pounds(Deere 2013). This represents both the state-of-the-art as well as one of the largest combines currently available. The combine used for benchmarks in comparison to the proposed harvest system is a smaller model from this series, the S550. These combines feature several options that provide the first steps of automation. Autosteer, GPS guidance, and detailed yield mapping are all part of the first steps towards a fully automated system, but still require a human operator at all times.

Figure 6: John Deere S690(“John Deere Innovations Recognized at Spain’s Top Agricultural Trade Fair” 2013)

Other companies have also made strides towards unmanned agriculture. For example, Kinze has partnered with Jaybridge Robotics to develop an autonomous grain cart system. This allows a tractor pulling a grain cart to drive alongside a combine, receive the grain being unloaded from the combine, and return to the edge of the field without human control(Jaybridge.com 2012).

2.3 Agricultural Economics

The economics of agricultural production is a well-researched field, and farm machinery costs are generally well understood. Often, machinery costs are calculated for an entire crop with each field operation from disking and tilling through harvesting(Burrows and Siemens 1974). This method allows for a comprehensive look at machinery costs, including timeliness losses (a loss in production due the reduced growing season of a late planting(Bargen 1980).) These methods show the effect of various machines, with larger, more expensive machines allowing for faster planting and harvest times, ultimately reducing timeliness losses.

Individual machine costs have also been thoroughly studied. Total machine costs are broken into fixed or ownership costs and variable or operating costs. Fixed costs include depreciation, finance, taxes, insurance, and housing. This list does not include purchase price because that cost is factored into the depreciation cost. Total depreciation is the purchase price minus the salvage value at the end of its life, and represents the decline in value caused by age and usage. Variable costs include repair and maintenance, fuel, lubrication, and labor. Repair and maintenance costs were calculated using formulas from Bowers and Hunt(Bowers 1970) determined by surveying farmers and developing a maintenance cost schedule based on total hours of usage.

Chapter 3. Conventional Harvest Method

Combine harvesters are used to harvest a multitude of crops ranging from common crops like corn, wheat and barley to more exotic grains like milo, sunflowers, canola, and mustard. This chapter will present the basics of corn production, as well as a history of combine harvesters.

3.1 Corn Physiology

Corn is the most prevalent crop in America measured by acre and bushel. In 2012, 96.95 million acres of corn were planted, with 87.72 million acres harvested for grain(National Agricultural Statistics Service 2012b). The estimated yield for 2012 is over 10 billion bushels. The vast majority of this is #2 field corn, the agricultural commodity used in ethanol production, livestock feed, and various other corn products. Corn plants have a tall (~8 ft.) bamboo-like stalk usually with one ear, with each ear containing several hundred kernels. The cob is roughly one inch in diameter and forms the center of the ear, with individual kernels protruding from the cob. Current corn harvesting technology for #2 field corn is focused solely on separating the kernels from the rest of the plant.

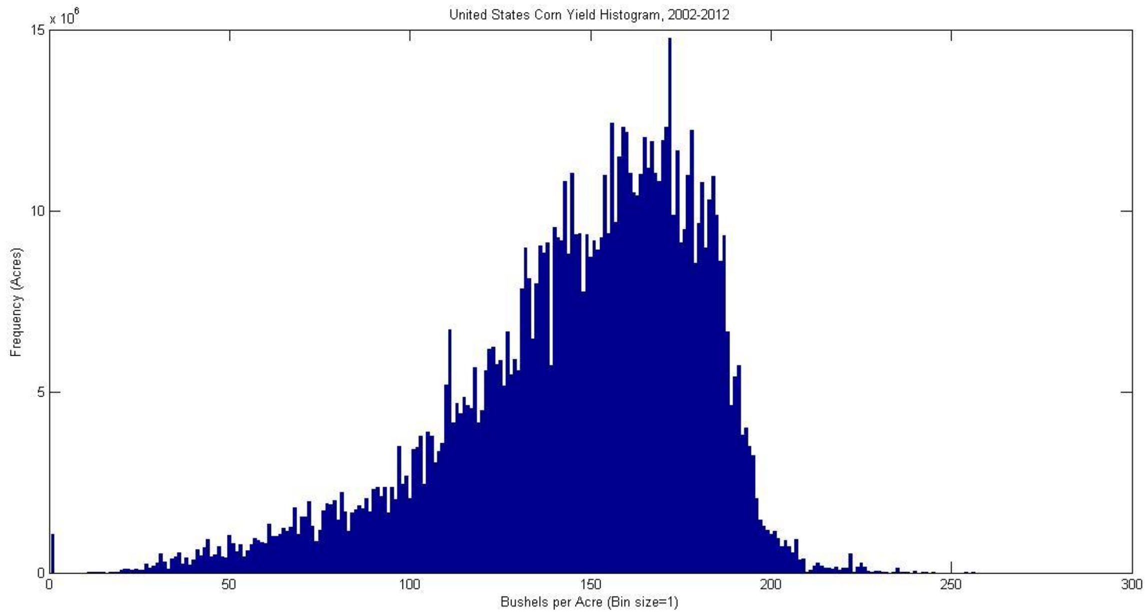
Corn is planted in widely spaced rows, ranging from 15 to 36 inches, but most typically planted in 30-inch rows(National Agricultural Statistics Service 2012b). It is typically planted in mid-May, and has a 90-120 day growing season, and the grain harvested in the late fall after the stalks have died and the kernels have dried on the ear, as seen in Figure 8.

Figure 7: Corn field in mid-season(Fishhawk 2013)

Figure 8: Corn field at harvest(Adams 2013)

Corn yield is measured in bushels per acre, and yield can vary widely not just between regions but can also vary at different areas inside of a field. The highest yields in America are in

Iowa, and the 10-year high yield for a county in Iowa is 204 bushels per acre(Brien 2013). The average yield for the United States as a whole in 2012 was 123.4 bushels per acre(National Corn Growers Association 2013). For the purposes of this thesis, the maximum expected yield is assumed to be 200 bushels per acre. As seen in Figure 9, almost all of the corn acres harvested in the United States yields less than 200 bushels per acre(National Agricultural Statistics Service



2012c), making this a valid assumption for design considerations.

Figure 9: Histogram of US Corn Yields (National Agricultural Statistics Service 2012c)

Number 2 field corn has a defined set of physical characteristics. This corn contains 15.5% moisture by weight, a weight of 56 pounds per bushel, a maximum of 3% broken kernels and debris, and maximum of 5% damaged kernels(United States Department of Agriculture 1996). The moisture content of this corn is a function of its maturity at harvest time. As the grain matures and the stalks die, the corn dries in the field. In ideal conditions, once the corn reached 15.5% moisture by weight, it would be harvested in the field(Wiatrak and Frederick 2013). However, the combination of inclement weather, equipment and labor availability, and the end of the harvest season often force farmers to harvest corn at higher moisture content, which must then be dried. Despite this, all calculations in this thesis will use 56 pound per bushel corn. The dried stalks, which make up the material other than grain (MOG) that a harvester must also process, are assumed to have equal dry matter weight to the grain that is harvested. The 15.5% moisture content of the kernels leaves 84.5% dry matter, therefor stalks are assumed to weigh 84.5% of the harvested grain.

3.2 Harvest History

Historically, corn and small grain harvest took place in three steps: reaping, threshing, and winnowing. As with modern harvesting techniques, the vast majority of historical harvesting methods were concerned with separating the stalk from the ground, the ears from the stalk, and the kernels from the ear. For corn harvest, reaping is the process of separating the stalk from the ground. Threshing is separating the kernels from the ear. Finally, winnowing is the process of separating the detritus like cob matter and corn silk from the grain. Examining the historical methods for this gives a better understanding of the modern technique and provides a functional decomposition of any future autonomous harvesting system.

3.2.1. Reaping

Reaping is the process of physically removing the stalk from the ground. Before mechanization, this process was performed by hand with a corn sickle, which is comprised of a short curved blade on a short handle. Corn stalks were stacked into shocks and left in the field to dry. Early mechanical reapers used cutter bars to cut the stalks, which were then bound into shocks. In both methods, it was necessary for the shocks to be left in the field to dry before threshing.

3.2.2. Threshing

Threshing traditionally refers to removing grain from chaff. In corn harvesting, the process is slightly more complicated than the processes in other grains. Ears are covered by leaves called shucks, which need to be removed before the grain can be removed from the cob. This process is referred to as shucking and was usually done by hand. Once the shucks have been removed, the kernels were removed by hand or the ears were placed into a sheller, which mechanically removed the kernels from the cob. Smaller versions of shellers were run by a hand crank, while larger ones were powered by horses or stationary engines.

3.2.3. Winnowing

Winnowing is the process by which detritus from harvest is removed from the desired grain, mostly the chaff surrounding seeds. Though corn is not surrounded by chaff, this process is important in other grains like wheat. Winnowing traditionally was performed by tossing or shaking grain off of handheld platform, allowing it to fall to the ground through a light wind or moving air provided by a fan. This would blow the chaff away from the heavier grain, separating the two.

3.3 Mechanization history

The early 20th century was a period of rapid mechanization throughout society. It witnessed the birth of early cars like the Ford Model T and advances in weaponry like the tanks and machine guns of World War I. Agriculture was not excluded from this industrialization. Starting with horse drawn equipment and progressing to steam engines and then finally to tractors powered by gasoline and diesel, agriculturalists adopted new technologies that allowed them to farm more land, produce higher yields, and reduce labor needed to work the fields. This combination of factors allowed farmers to economically justify the purchase of expensive new machinery.

As early as the 1830s, inventors had constructed mechanical harvesters, such as Cyrus McCormick's reaper shown in Figure 10. Early models were pulled by horse trains and powered by a bullwheel, using the motion across the ground to drive cutter bars other powered systems needed to reap and gather grain. Separate threshers were used to separate the grain from the straw. These early inventions worked in small grains such as wheat, barley, and oats. However, the physical differences between small grains and corn required development of separate technologies.

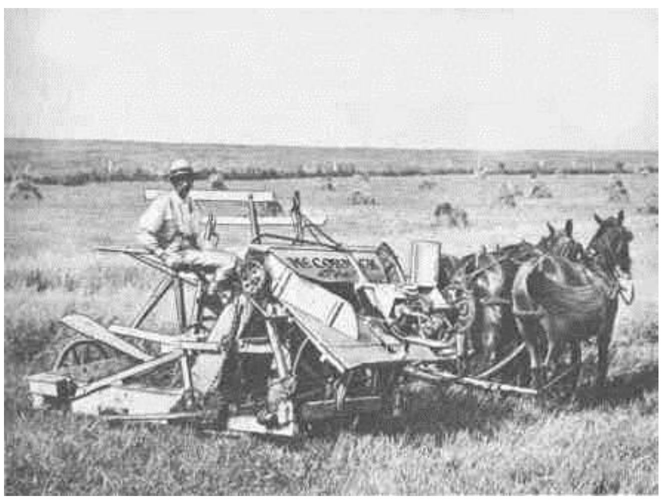


Figure 10: The McCormick Reaper(P. Wong 1992)

Mechanization of the corn harvest took longer to develop, as shucking the ears creates a more complex problem than that of small grains. An early corn picker had been invented in 1850(Colbert 2000), but until the end of the 19th century, most inventions were experimental and did not experience much commercial success. These early pickers cut stalks and bound them together, but did not remove ears from stalks. In 1928(Colbert 2000), the first pull-behind corn picker was introduced, which was pulled behind a tractor and powered with a power take-off (PTO) shaft. In 1930(Colbert 2000), a tractor mounted two-row picker was introduced. These pickers allowed farmers to pick more land using less labor than previous methods. Horse drawn pickers required several men to drive the horses and work with the picker itself, and the expense of the machine led many farmers to continue to harvest by hand. The introduction of tractor-powered pickers finally tipped the economics of picking in favor of mechanization(Colbert 2000).

It is important to note that economics is the driving force behind machinery decisions for almost every farmer. "Labor saving" devices have been patented for hundreds of years, but very few devices become a commercial success until a device can pay for itself. Hand husking was hard work and lasted several weeks. Corn was picked by hand from sunup to sundown by farmers and hired labor. A good day of harvesting was 80-100 bushels of corn for one man, which was equivalent to 2-3 acres of corn(Colbert 2000). These acres were harvested in all conditions, with frost on the ears in the early morning that froze hands and snow on the ground that froze feet. The husks were rough, and working in the cool fall air often dried and cracked hands until they bled. Despite these harsh conditions, farmers continued to pick corn by hand. Early mechanical pickers were slower and far fussier than hand picking, often requiring repairs that would delay harvest by days and needing frequent maintenance and cleaning. By the time the systems had improved in the 1920s and early 1930s, low corn prices and the great depression and dust bowl squeezed farm budgets to the point that purchasing equipment was unfeasible for many. However, even during the hardships of the 1930s, the economic calculus tipped in favor of purchasing equipment for farmers(Colbert 2000). By the 1930s, the technology was both mature and advanced enough to provide convenient and reliable operation that generated enough revenue to pay for itself. Tractors saw a huge rise in use, from 246,000 tractors on farms in 1920 increasing to 920,000 used in 1930(Colbert 2000). This increase in on-farm power allowed implements with high power requirements like corn pickers to be used. Advances made by the 1940s in machine design for both the pickers and the tractors led to widespread adoption on farms across the US.

3.4 Modern Combines

In the 1938, the first modern combine was introduced("Massey Ferguson Celebrates the 75th Anniversary of the MH-20 – the World ' s First Self-propelled Combine Harvester" 2013). Combines did the work of several machines. While pull-behind and tractor-mounted combines exist, the large majority of combines are self-propelled. Unlike the previous harvesters and picker-shellers, modern combines can harvest both corn and small grain, needing only minor adjustments and a different cutting head.

In a modern combine reaping is accomplished at the header, a large platform attached to the front of the machine. For corn, reaping is mostly done with snapping rollers, a technology that has been used since the late 19th century. Snapping rollers grasp the stalk and pull it down while a plate on the head snaps the ear off, as shown in Figure 11. The ears are then collected by an auger and transported through the feederhouse to the threshing cylinder. This method minimizes the amount of stalks passed through the system, which improves the threshing efficiency. Combines with four, six, eight, and twelve row heads are common, with ground speeds determined mainly by crop throughput. Larger heads can harvest more corn in less passes, but the main consideration for header size is planting equipment. It's important to match header and planter equipment so that the rows in the field match up with the rows on head. If a farmer had an 8-row planter but used a 6 row head, the "guess" row (the space left between passes of the planter) would cause issues during harvest. In the larger operations, 12 and 24 row planters are common, and are used with 12 row heads. In smaller operations, 8 row planters are commonly

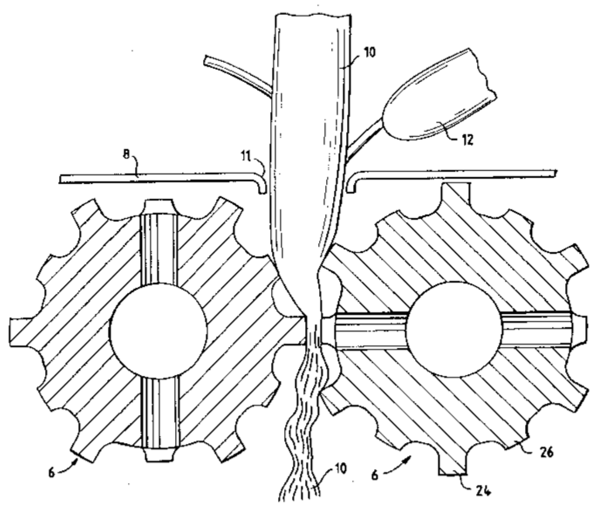


Figure 11: Snapping Rollers(Schoolman 1994)

used with 4 or 8 row heads, and 12 row planters are used with 4 or 6 row heads.

Threshing in a modern combine is performed by a threshing cylinder. These are usually 60cm or more in diameter("Combine Comparison Results"), with teeth or axial bars that rotate the material against a "concave" which is a concave grate or screen that separates the grain from stalk or ear. There are a multitude of designs for threshing, with several methods of passing material through the cylinder, multiple cylinder arrangements, and a variety of cylinder layouts inside the combine. Sample threshing cylinder layouts are shown below in Figure 12. The huge number of solutions is partly a function of the pros and cons of different methods for working in several different crops and also partly due to companies working around patents held by other agricultural manufacturing companies. The distance between the cylinder and the concave is adjustable, and can be tweaked for the specific crop being harvested and to reduce threshing losses. These concave adjustments are critical to a good harvest. If the concaves are left too open, insufficient threshing will take place, and the straw ejected from the combine will contain grain that should have been harvested. If the concaves are set too close to the cylinder, they will crack and otherwise damage the grain. After the grain has been threshed, it is passed out of the cylinder and into the winnowing section of the combine.

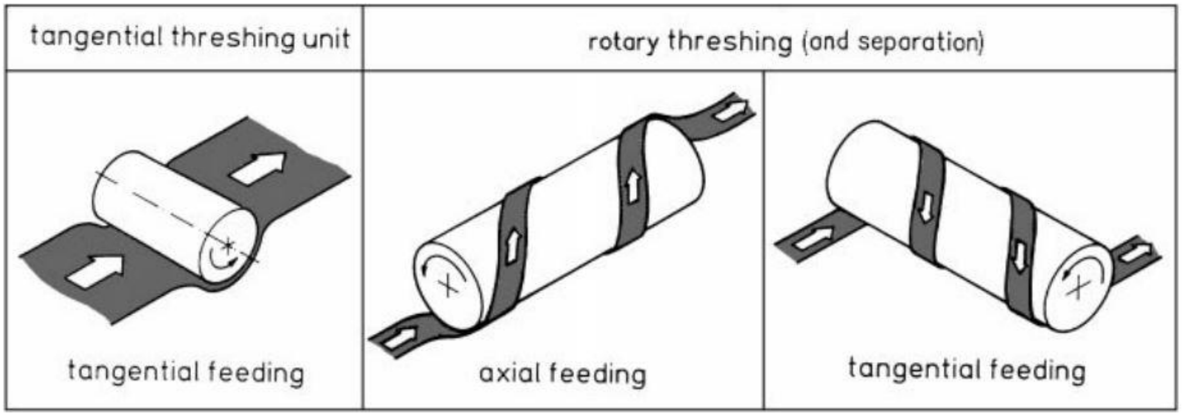


Figure 12: Threshing Cylinder Layouts(Stout et al. 1999)

Separating grain from straw and chaff in a combine takes place using several different methods. The first step in the process is the straw walker. The straw walker consists of large, toothed, widely spaced beams that walk the straw (when harvesting small grain) and hobs, husks, and any stalks that came through the header for corn. This motion pushes the unwanted material out the back of the combine, while shaking any grain onto the cleaning shoe below. The shoe consists of a chaffer and a sieve. These work much like traditional winnowing, using a fan to blow small, light detritus away from the grain. The chaffer shakes the grain through to the sieve, allowing the cleaned grain to be moved to a bulk storage tank. Material that is too heavy to be blown away but didn't make it through the sieve is directed back to the threshing cylinder to begin the process again, while the chaff sorted out by the winnowing process is also ejected from the rear of the combine.

This process has its roots in in the same processes used for centuries: cutting stalks from the ground, beating grain away from stalks, and blowing the chaff away from the grain. What separates the modern process from ancient is scale. A modern combine can harvest up to 5000 bushels an hour, while 150 years ago it took a man a whole day to merely pick 80-100 bushels(Colbert 2000). What was once backbreaking work, rife with bleeding hands, frozen feet, and miles of walking can now be done almost entirely hands-free, riding in a leather seat with heat and air conditioning, a radio, and even a refrigerator. These conveniences help improve the quality of living for combine operators, and some even improve productivity.

3.5 Grain Carts

When discussing harvest, it is important to note what happens to the grain once it is harvested by the combine. After reaching the bulk tank, grain is offloaded into a grain cart, used to move grain from the combine directly to bulk storage or to a waiting dump truck or tractor-trailer which is then taken to bulk storage. Grain carts often hold over 1000 bushels, come equipped with large floatation tires, and are pulled by tractors, all in an effort to reduce ground compaction and allow use in wet fields, where higher ground pressures would sink in the mud. These grain carts are another manpower requirement and waiting for them to service the combine reduces the combine's field efficiency. These are both important considerations when dealing with harvest automation. Kinze, an agricultural equipment manufacturer, has partnered with Jaybridge Robotics to develop an autonomous tractor and grain cart system shown in Figure 13 but this technology is still in the development phase(Jaybridge.com 2012). Grain carts represent a significant opportunity to improve the work efficiency of a harvest system.

Figure 13: Kinze Autonomous Grain Cart(Ford 2012)

3.6 Harvest Infrastructure

After being offloaded into a grain cart, the grain is then loaded into a dump truck or tractor-trailer to be hauled to either an on-farm grain bin or a local grain elevator. This point represents the interface between any autonomous system discussed in this thesis and the rest of harvest process. At this point, grain leaves the farm and enters the agriculture infrastructure, going to grain bins and grain elevators, tractor-trailers and barges, feed mills, ethanol plants, and the feed bunks of livestock around the country. An example of one path for corn from field to consumer is shown in Figure 14.

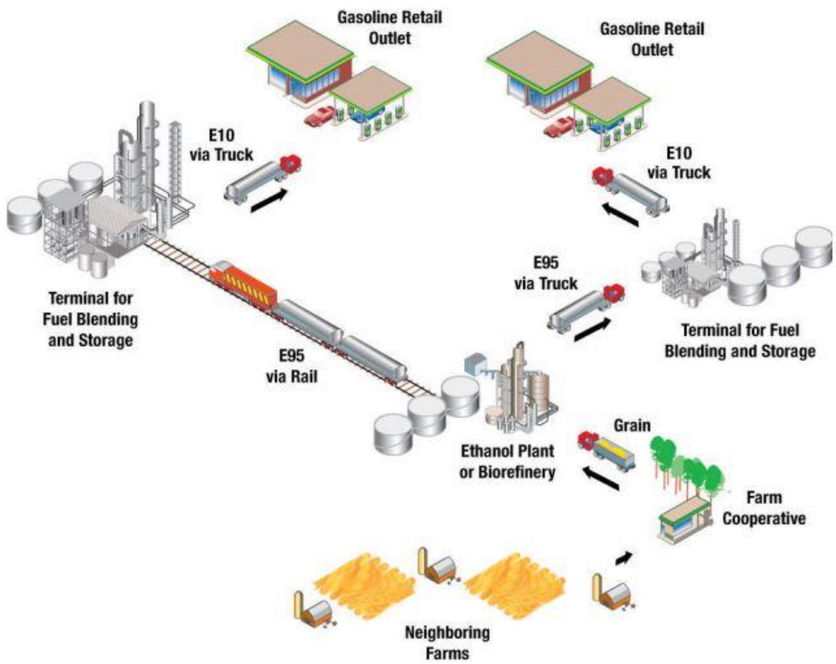


Figure 14: Field-to-consumer process for ethanol(US Department of Agriculture Agricultural Marketing Service 2007)

3.7 Current Automation

Autonomous agriculture is a rapidly developing field, with several useful contributions to farm equipment made in the last 20 years. GPS technologies are applied to all aspects of crop farming, from planting to harvest. The advent of cheap and reliable GPS allowed for new uses in equipment. The use of automation allows for improved planting, eliminating skips and overlaps in the field. Spraying and other crop care is also improved by monitoring exactly where the spray boom has passed through the field. Harvesting can follow the exact path laid down by the planter, eliminating any guesswork on the operator's part on which rows to follow. Agriculture quickly adopted GPS in the form of manual guidance, with the first devices reaching the market in 1995(Heraud and Lange 2009). For manual guidance, a GPS device follows paths defined by an operator's first pass or manually entered as coordinates. Each subsequent path is created by offsetting the new path by the implement width. These paths are then communicated by a light-bar, indicating to the operator if they need to turn right or left to stay on the desired path. Automatic guidance, where the steering is controlled by computer, was first released in 1997(Heraud and Lange 2009). There are a few approaches for automatic guidance. In one, steering input is provided to the drive-by-wire system to follow computer provided paths(John Deere 2013b). Another technology uses an electric motor to turn the steering wheel(Trimble 2013), a solution that is easier to retrofit onto existing equipment.

Autosteer technologies, like much of precision agriculture, require better spatial resolution than the 4 to 5 meters offered by standard GPS. To overcome this error, several methods of signal correction are used. Some manufacturers use differential GPS (dGPS), relying on a base station to provide correction for fields and other localized areas(Heraud and Lange 2009). Other technologies rely on wide area correction broadcasts or real time kinematic correction(Heraud and Lange 2009). Both methods considerably improve accuracy, with current real time kinematic systems providing accuracy of ±1 inch("John Deere Reciever Costs" 2013).

The increased use of GPS sensing, coupled with the decreasing cost of other sensors, has led to a dramatic increase in other forms of information gathering and crop health monitoring. Increased control on planters can give precise planting densities, airplanes carrying multi-spectral camera equipment can monitor crop health, and combines can create yield maps showing exactly how much grain is harvested at each spot in the field. Allowing farmers to move crop management into the information age has had an impact that rivals autonomous equipment. An increase in the quality of information available to farmers allows them to make decisions based on science, not intuition. This has huge implications for crop management. Aerial crop maps can provide crop health information at a resolution of 1 meter, allowing farmers to precisely apply fertilizer, reducing input costs(Jayroe, Baker, and Greenwalt 2005). All of these advances are made possible by the increased use of computers and decreasing cost of sensing.

3.7.1. Degrees of Autonomy

Current development in robotics and automation has led to several degrees of autonomy. At the lowest level, remote controlled vehicles are operated by a human and provide no feedback to the operator. Teleoperated robots are devices that have no on-board decision making, and are completely controlled by a human, but send feedback in the form of video or other sensing to the operator. Co-operative and semi-autonomous robots have varying degrees of self-control, but rely on human interaction for some functions. Fully autonomous vehicles have complete self-control and do not need human interaction to operate(National Institute of Standards and Technology 2004). Current state of the art in agricultural machinery is at a semi-autonomous level, with limited exceptions. Even for equipment with accurate dGPS and autosteer, a human operator is required to be in the cab. Some systems such as the Kinze grain cart system have demonstrated full autonomy, but are not yet available to the public.

Chapter 4. Economic Analysis

Examining the feasibility of any new product or system requires investigating the economics of ownership and operation. In the case of the autonomous harvest system proposed in this thesis, the benefits of the system must outweigh that of the alternative conventional system. Because the economics of the system are essential to its success, a careful analysis of the economics of harvesting provides important design benchmarks. In order to make this initial economic analysis, a rudimentary approximation of the system will be assumed to provide the first iteration of the design benchmarks. These design benchmarks will then be used to further refine the conceptual design in Chapter 5.

4.1 Economic Analysis for Farm Operators

The decision to purchase agricultural equipment presents many options for a farmer. New versus used, capital outlay versus increased productivity, and a host of other questions must be considered to make an informed decision. Many papers exist (Burrows and Siemens 1974; Ozkan and Edwards 1986),(Edwards 1989) providing models and analysis for determining appropriate machinery numbers and sizing. In these studies, the researchers looked at the total cost of capital, labor, maintenance and service, and timeliness costs, which approximates the total cost of ownership to the farmer. Harvesters provide value to the farmer in the form of grain ready for sale or use, which has value based on the current market. When evaluating the value provided by the harvester, the metric used will be total value of grain minus the total cost of ownership. This provides a consistent comparison across various equipment and gives insight to the factors that drive business decision making.

When faced with the task of harvesting grain, a farmer has two options: purchase equipment or hire a custom harvesting operation. In order to conduct an enterprise level analysis of the proposed autonomous system versus current harvesting technology, a comparison will be made with two newly purchased systems, a conventional John Deere S550 harvester and a system comprised of multiple small autonomous harvesters. Economic analysis will also be conducted for an autonomous harvester of conventional size to evaluate the viability of the smaller system against similar technological advancements. For this analysis, the use of multiple harvesters provides roughly equivalent harvesting capacity as the large conventional harvester. The effect of using one harvester is discussed in Section 4.5. Custom harvesting operations represent a viable alternative to owning equipment, but the analysis presented here assumes that the farmer has decided to purchase equipment. A separate analysis of the proposed autonomous system for custom harvesters is provided in Section 6.2.

Farm purchasing decisions take several factors into consideration. Beyond just purchase price and sizing, things like brand loyalty, maintenance requirements, increased productivity, and integration into existing operations all play a large role in the decision making of a farmer. Convincing a farmer to purchase a new technology requires showing a clear increase in value over the next best option. In order to develop a new autonomous harvesting technology, a clear increase in value returned to the producer must be demonstrated, with consideration given to the factors that are important to a farmer.

4.1.1. Opportunity Cost

In this analysis, the opportunity cost, or next best option, for the proposed system is a conventional combine. The costs and benefits of this technology are well understood, and represent an appropriate benchmark for any new harvester design. This comparison also reflects the purchasing decision faced by a farmer when choosing between new or existing technology. By using combines as both the next best option for farmers as well as the benchmark to beat for autonomous harvester design, a set of design parameters can be developed that meet both the functional and economic needs of agricultural producers.

4.1.2. Cost of Ownership

The total cost of ownership represents far more than purchase price. Reducing the labor needed to complete a task is not enough reason for purchase for most farmers. While usually not performed using spreadsheets and rigorous methods in most cases, farmers do evaluate the economic consequences of purchasing new equipment. As an example, several robotic systems exist to autonomously milk cows. However, each robot costs hundreds of thousands of dollars, only milks 60-100 cows, and requires either completely new barns and a new milking parlor or an extensive redesign(Grobart 2012)(Haan, Stuart, and Schewe 2009). So while milking is hard, dirty work lasting 15 hours per day, 365 days per year, few farmers can justify spending upwards of one million dollars to milk an average sized herd even if the system makes the work significantly easier(Rotz, Coiner, and Soder 2003). For field equipment, the farmer’s cost of ownership calculation includes important factors like downtime and repair budgets that are overlooked when looking solely at purchase price.

4.2 Measuring Return from Equipment

The metric for establishing the superior harvest method in this analysis is the minimum total cost. These harvesters are one part of a larger process that sows, cultivates, and harvests grain. Because a combine is one small part of the fleet of agricultural equipment that affects crop yield, more traditional equipment evaluation methods such as break-even point, payback period, and return on investment are ill suited for evaluating the economic effectiveness of a harvester. The method used in this paper is similar to the method used by Ozkan and Edwards (Ozkan and Edwards 1986), which subtracts the total cost of ownership from a theoretical gross crop receipt. This method considers both the real costs paid by the farmer and timeliness losses incurred from harvesting crops too late. However, unlike the Ozkan and Edwards paper, the analysis presented here is independent of other machinery operations such as planting and spraying so timeliness losses are only due to harvest timing. Without differences in planting, cultivating, or spraying the gross crop receipts for each method is the same, except for timeliness losses. These timeliness losses will be treated as an operating cost for each system, and the economic effectiveness of the system will be based solely on the total cost of ownership.

4.3 Comparison of Current Methods to Proposed Method

A detailed economic comparison between a variety of methods will provide insight in the feasibility of the proposed system. Three methods are compared here: the proposed small harvester system using three fully autonomous harvesters; a conventional harvester operated by a human; and a fully autonomous combine of conventional design. These three systems were chosen in order to evaluate both the effectiveness of an autonomous system versus a conventional system as well as examining the effect of size on an autonomous system.

4.3.1. Assumptions

Because the economic analysis will drive the conceptual design of the proposed harvest system, some basic assumptions must be made to perform a first order analysis. These assumptions serve to limit the possible design space so that the economic analysis is relevant to the conceptual design.

The impetus for this research is the evaluation of smaller autonomous harvesters, and the first and most important assumption in this research is the size of each harvester. For this first pass analysis, the size of each harvester is assumed to be roughly one-third the size of current equipment. Many, if not all, of the systems on a combine do not scale linearly, but for the purposes of the economic analysis, weight, horsepower and throughput are assumed to be roughly one third of the benchmark numbers. Using the John Deere S550 as a baseline, with a weight of 30,980 pounds and rated at 271 horsepower, the autonomous system will be designed for 10,000 pounds and 90 horsepower.

At this smaller size, it is also assumed that three harvesters will be used in tandem. Cooperative robotics is a well-researched field, and several researchers have discussed the use of this technology in agriculture(Vougioukas 2012) (Johnson et al. 2009)(D. Bochtis et al. 2007). The use of three harvesters, as well as optimized path planning, should provide similar field harvesting times. The proposed system has the ability to utilize more and less harvesters, but three was chosen for this analysis in order to provide similar harvest times across each system.

At some points in this analysis, it is necessary to assume both a field size and a farm size. For this economic analysis, the field size is assumed to be a quarter section, or 160 acres in a square field 1320 feet on each side. This is the standard field layout for much of the United States, especially the Midwest, which produces much of the corn in the US(“The Public Land Survey System (PLSS)” 2013). The farm size is assumed to be 640 acres, or one section. This size is chosen because it matches the US weighted median crop farm size(Macdonald 2011).

4.3.2. Total Cost of Ownership

The analysis presented here will evaluate the costs faced by the farmer in purchasing, owning, and operating harvesting equipment. Some costs will be approximated using American Society of Agricultural and Biological Engineers (ASABE) standards or other methods discussed in detail below. The cost for these machines is estimated over a 10-year lifespan for the vehicle. For this period, annual fixed and variable costs will be estimated, and then net present value will be calculated. This method will provide an approximation for costs for the life span of the vehicle and allow for a consistent comparison of costs that accumulate with use, such as total maintenance costs.

4.3.2.1. Fixed Costs

Calculating the total cost of ownership for conventional harvesters has been done many times(Edwards 2009), so a brief analysis will be presented here. Capital costs are the first and most obvious outlay in the ownership costs of a harvester. Both John Deere and Case IH combines have a base price of approximately $285,000 for their smallest combines(“John Deere S550 Build” 2013)(“Axial-Flow 5088 Build” 2013), which produce about 270 horsepower. At the opposite end of the spectrum, the top of the line combines for John Deere and Case IH produce about 500 horsepower and cost approximately $450,000(“AF 9230 Build Page” 2013)(Deere 2013). Headers, the front attachment used for reaping, vary in size and cost, but a six row header is the smallest available new attachment and costs approximately $50,000(“606C Build Page” 2013). Eight row headers cost approximately $70,000(“608C Build Page” 2013), and twelve row headers cost about $100,000(“612C Build Page” 2013). As with most products, the ability to up-option a combine significantly increases the purchase price but as a general guideline the cost for a new, complete system ranges somewhere between $350,000 and $650,000. For the autonomous harvester of conventional size, the system is assumed to cost $50,000 more than a conventional system. This cost is roughly equivalent to price needed to convert a vehicle to full autonomy, based on Google’s cost for their fully autonomous cars. Their vehicles cost $150,000 with $70,000 for a Light Detection and Ranging (LIDAR) that provides information about distance to surroundings, and $25,000 for the car, neither of which will be used in the combine system(Woodyard 2014).

In order to maintain competitiveness with current systems, the target cost for one machine is $125,000. Using a profit margin of 20%, the manufacturing costs of the machine should not exceed $100,000. Of this $100,000, approximately $25,000 is for sensing and automation equipment, including cameras, radar units, and drive-by-wire actuators. The remaining $75,000 is for the raw materials, manufacturing, and overhead costs. Chicago Mercantile Exchange futures pricing gives an estimated steel cost for the machine of $2,890(Chicago Mercantile Exchange).

4.3.2.1.1. Depreciation

While the capital cost is a major financial outlay for the operator, capital costs do not factor into the total cost of ownership. Depreciation is the cost that reflects the machine value that has been lost due to owning and operating the machine. Depreciation is calculated by subtracting the salvage value (also known as the remaining value, or RV in Equation 4.1) from the purchase price, it represented the value lost by use and aging of the equipment. The remaining value is the expected sale price of the equipment at the end of its service life. The American Society of Agricultural and Biological Engineers calculate the remaining value as a percentage of the list price using Equation 4.1 shown below(American Society of Agricultural and Biological Engineers 2011). The coefficients C1, C2, and C3, are 1.132, 0.165, and 0.0079, respectively and are the result of curve fitting based on empirical data collected at farm auctions. The variable n and h represent the years of use and average hours of use per year. The average annual use is 78.2 hours for the proposed system, 94.5 hours for a conventional system, and 60.5 hours for an autonomous system of conventional size.

$$RV_n = 100[C1 - C2(n^{0.5}) - C3(h^{0.5)})]^2 \qquad (4.1)$$

For the proposed system, the salvage value is 29.2% of the purchase price, for a depreciation cost of $265,507. The conventional system will have 28.5% of its initial value remaining at the end of its service life giving $275,544 in depreciation, and the autonomous system of conventional size will have a remaining value of 30.3% of its initial value for a deprecation of $303,180.

4.3.2.1.2. Finance Costs

The financing cost of equipment is also important to factor into the cost of ownership. A Farm Credit equipment loan has current rates between 3.15% and 4.1% depending on the length of the loan("Equipment Loan Rates" 2013). Using a 4.1% interest rate over a five-year period, a farmer can expect to spend an additional $57,019 on interest for a loan on the proposed $375,000 system. For a conventional combine with a $385,000 loan the finance costs would be $58,539, and the autonomous system of conventional size would require $66,142 in finance costs for a $435,000 system.

4.3.2.1.3. Taxes and Insurance

In addition to the purchasing costs, several ancillary costs must be considered when calculating the fixed cost of ownership. Taxes, insurance, and housing each represent a small portion of the total cost of ownership, but are included here for a more complete analysis. Laws on personal property taxes for farm equipment vary from region to region. In Virginia, farm equipment is exempt from personal property taxes(*VA Code § 58.1-3505*), and many other states have personal property tax exemptions for agricultural equipment(Perry and Nixon 2002). For this analysis, the harvest equipment will be assumed to be exempt from personal property taxes.

Risk management tools such as insurance are based on the purchase price of the equipment if not part of a more comprehensive farm-wide insurance policy. An insurance policy for individual pieces of equipment will be used for the purpose of analysis, at a rate of 0.5% of purchase price(Edwards 2009). This rate gives a cost of $1,875 annually for the proposed system, $1,925 for the conventional system, and $2,175 for the large autonomous system.

4.3.2.1.4. Storage

Machinery storage is an important factor in the resale or salvage value and in reducing maintenance costs. When factoring higher value retention, lower maintenance costs, and less downtime, storage inside can save up to 6.7% of the initial purchase price per year as compared to storage outside(R. Grisso 2009). However, equipment storage has an associated cost. This cost is approximated as $1.25 per square foot of storage space(R. Grisso 2009). This cost distributes the purchase price of a building over the square footage and lifespan of the building. The footprint of the proposed system is 18.5 feet long by 7.5 feet wide, as discussed in section 5.4, for a footprint of 138.75 square feet for one harvester. For a three-harvester system, the overall footprint is 416.255 square feet, resulting in a total annual storage cost of $520.31. A John Deere 680S is approximately 13 feet wide and 37 feet long with a corn head, for a footprint of 481 square feet and an annual storage cost of $601.25 for both the conventional system and the large autonomous system.

Purchase price, finance costs, taxes, insurance, and housing represent the fixed costs of ownership for both conventional harvesters and the proposed system. These costs are independent of operation, and will be occurred whether the machines sit idle or are used for hundreds of hours per year. For a conventional and large autonomous system, these costs are $399,775 and $434,391, respectively. For the proposed system these costs are $382,515, as shown in Table 1.

Table 1: Fixed cost comparison

Fixed Costs												
	Proposed				Conventional				Autonomous Conventional			
	Per acre	Per hour	Annual	Lifetime Total	Per acre	Per hour	Annual	Lifetime Total	Per acre	Per hour	Annual	Lifetime Total
Interest	$6.31	$51.63	$4,038.79	$40,387.89	$6.48	$43.87	$4,146.49	$41,464.90	$7.32	$49.57	$4,685.00	$46,849.95
Depreciation	$49.71	$406.76	$31,817.43	$318,174.33	$52.04	$352.35	$33,304.77	$333,047.72	$56.22	$380.63	$35,977.85	$359,778.53
Insurance	$2.93	$23.97	$1,875.00	$18,750.00	$3.01	$20.37	$1,925.00	$19,250.00	$3.40	$23.01	$2,175.00	$21,750.00
Housing	$0.81	$6.65	$520.31	$5,203.13	$0.94	$6.36	$601.25	$6,012.50	$0.94	$6.36	$601.25	$6,012.50
Subtotal	**$59.77**	**$489.01**	**$38,251.53**	**$382,515.34**	**$62.46**	**$422.94**	**$39,977.51**	**$399,775.12**	**$67.87**	**$459.57**	**$43,439.10**	**$434,390.98**

For the proposed autonomous system, all of the fixed costs of ownership are less expensive than both the conventional system and an autonomous system of conventional size. This is a direct result of the lower purchase price, which gives lower depreciation, lower finance costs, and lower insurance costs.

4.3.2.2. Variable Costs

The variable costs, or those which vary with operation, are composed of repairs and maintenance, fuel, lubrication, and labor. These vary largely with the hours operated. Some vary on a per hour basis, such as fuel and labor, while repairs and maintenance are a function of the cumulative hours of machine operation.

4.3.2.2.1. Repair and Maintenance

Repair and maintenance represent an important component of variable cost. Cost estimates are based on a survey of farmers, and is calculated a percentage of the new list price. In order to calculate maintenance costs, a 10-year lifespan will be assumed. Annual separator hours are determined using equation 4.2, the total farm acreage is divided by combine coverage in acres per hour. Engine hours are estimated by dividing separator hours by the field efficiency. With four 160-acre fields and three combines harvesting 3.03 acres per hour, the harvesters will run for 78.2 hours per year.

$$Annual\ Separator\ Hours = \frac{field\ size * number\ of\ fields}{harvest\ rate * number\ of\ combines} \qquad (4.2)$$

After 10 years, this gives a total of 782 accumulated hours. Table 2 lists the total maintenance costs for equipment as a function of total accumulated hours. This was taken from the Iowa State Extension service(Edwards 2009), and is a useful tool in estimating this cost. Using Table 2, the maintenance costs for the autonomous system are 2.2% of the new list price. The total list price for this 3-combine system is estimated to be $375,000 giving a total maintenance cost of $8305.56. Distributing this across the years and acres harvested gives a cost of $1.30 per acre per year, $3.54 per hour per year for each machine, and $10.62 per hour, total.

Table 2: Machinery maintenance schedule

Type of Machinery	Accumulated Hours									
	300	600	900	1200	1500	1800	2100	2400	2700	3000
Forage Harvester (SP)	0%	1%	2%	4%	7%	10%	13%	17%	22%	27%
Combine (SP)	0%	1%	3%	6%	9%	14%	19%	25%	32%	40%
Windrower (SP)	1%	2%	5%	9%	14%	19%	26%	35%	44%	54%
Cotton Picker (SP)	1%	4%	9%	15%	23%	32%	42%	53%	66%	79%

Maintenance costs for a conventional system are calculated in the same manner. A conventional system with a 12 row head moving 3.8 miles per hour can harvest 9.8 acres per hour(Iowa State University Extension Service 2009). Including 70% field efficiency, this gives an annual hourly usage of 93.3 hours per year for a 640-acre farm. This gives an accumulated maintenance cost of 3.33% of the new list price, or $13,290.98 for a $285,000 combine and a $100,000 header. This is a rate of $2.08 per acre per year, or $14.06 per hour.

No publicly available information exists detailing the changing maintenance costs for newer agricultural equipment. Current maintenance schedules are constructed with data collected in 1966 and updated in 1991(Lazarus 2008). While these numbers may fail to accurately reflect changing costs, they are the best available estimate, and serve as a rough guideline. Further exploration into the effects of increasing technology on maintenance costs is a source of future work.

4.3.2.2.2. Fuel Costs

Fuel costs are calculated in greater detail in section 5.3.7, where total fuel usage per hour was determined to be 4.06 gallons per hour. The current national average price for off-road diesel fuel is $3.42 per gallon(U.S. Energy Information Administration 2013). Using a harvest rate of 3.03 acres per hour, this gives a per-acre cost of $4.59 or an hourly cost of $13.91 per hour per machine, or $41.73 per hour for the entire harvest system. Using 78.2 annual hours of operation calculated above, the annual fuel cost for all three machines is $3264.52. The present value for fuel cost accrued for 10 year period is done using a rate of inflation of 3% and an annual fuel cost increase of 15%, calculated using historic data("Gas Price Historical Data" 2013). The total net present value for 10 years of fuel usage is $49320.03.

For a conventional system fuel usage is 1.6 gallons per hour(Colorado State University Extension Service), it can harvest 9.8 acres per hour(Iowa State University Extension Service 2009), and has a 70% field efficiency. This gives a per acre cost of $5.48, an hourly cost of $51.58, and a total 10 year net present fuel cost of $72711.18.

4.3.2.2.3. Lubrication

Lubrication costs are assumed to be 15% of fuel costs(Edwards 2009). For the proposed system on a 640-acre farm, this results in a per-acre cost of $.77, an hourly cost of $6.26, and a 10-year total cost of $7398.01. For a conventional system, the per-acre cost of $1.13, an hourly cost of $7.73, and a 10 year total cost of $10.906.68.

4.3.2.2.4. Labor

Estimating labor costs are difficult for the proposed system. Very few systems are truly fully autonomous, and even though the proposed individual harvesters have no direct human operator, they will not operate completely unsupervised. The model proposed for this system is frequently referred to as a “human oracle,” where one human can supervise several different autonomous vehicles, which defer to human guidance when confronted with situations that require human input, such as alerts about safety systems or unfamiliar or unnavigable terrain. In one agricultural system, researchers estimate that this method of autonomous system supervision can improve human productivity by a factor of four, and one human can supervise four or more robots at once(Stentz et al.). This supervision scheme requires one human to oversee several robots, so for this system, one person is required to be present while the system is operating. Therefore, the annual labor requirement for this system is 78.2 hours per year, plus an adjustment for time required to service the system. Labor usually exceeds machine time by 10-20%(Edwards 2009), and to adjust for this, total machine hours will be increased by 15%, for a total of 89.93 hours. Farm labor rates vary from location to location and by job type, but Midwest crop farms have an average wage rate of $12.35 per hour during harvest time(National Agricultural Statistics Service 2012a). For the purposes of this analysis, the rate will be adjusted to $15 per hour to reflect the higher skill needed to operate an autonomous system. This labor rate results in an annual labor cost of $1349.33 for a 3-harvester system on a 640-acre farm. This is a rate of 2.11 per acre, and a 10-year labor net present value of $13,493.33, assuming a 3% increase in both the labor rate and a 3% rate of inflation. For a conventional system using one harvester with a 12 row head on a 640-acre farm, the average rate of $12.35 and 107.3 annual hours were used in the calculation, returning an annual labor cost of $1325.01. For the conventional system, the per-acre rate is $2.07 and the 10-year net present value of labor costs is $13,250.15.

Labor rates for the proposed system may vary widely based on the number of machines used. An operator can supervise many harvesters, so labor costs can be divided among as few as one or as many as 6 to 8 systems. If one machine is used, the labor cost in the above analysis increases to $4,048 and $6.33 per acre. If 8 machines are used, the total labor cost is $506.00 for a per-acre rate of $0.79. This flexibility gives farmers the ability to tailor their machinery portfolio to their needs.

A comparison of variable costs for the two systems is shown below in Table 3. Costs are lower for the proposed system, due in large part to the reduced hours needed to harvest the crop. This is due to the higher field efficiency, and lowers the total maintenance costs, fuel costs, and lubrication costs. The labor costs for the autonomous system are higher because of the higher wages paid to the operator.

Table 3: Varible cost summary

Varible Costs												
	Proposed				Conventional				Autonomous Conventional			
	Per acre	Per hour	Annual	Lifetime Total	Per acre	Per hour	Annual	Lifetime Total	Per acre	Per hour	Annual	Lifetime Total
Maintenance	$1.30	$10.62	$830.56	$8,305.56	$2.08	$14.06	$1,329.10	$13,290.98	$0.70	$7.45	$450.76	$4,507.62
Fuel	$4.69	$38.41	$3,004.18	$45,386.71	$7.38	$49.96	$4,722.25	$71,343.15	$5.36	$56.64	$5,180.53	$51,805.32
Lubrication	$0.70	$5.76	$450.63	$6,808.01	$1.11	$7.49	$708.34	$10,701.47	$0.80	$8.50	$514.35	$7,770.80
Labor	$2.11	$15.00	$1,349.33	$13,493.33	$2.10	$12.35	$1,342.45	$13,424.49	$1.63	$15.00	$1,044.38	$10,443.76
Subtotal	**$8.80**	**$69.78**	**$5,634.69**	**$73,993.61**	**$12.66**	**$83.86**	**$8,102.13**	**$108,760.09**	**$8.50**	**$87.58**	**$7,190.02**	**$74,527.49**

An overall comparison of costs is shown below in Table 4. The ten-year difference in costs is $52,026.25 less than the conventional system and $52,409.52 less than the autonomous system of conventional size in favor of the proposed system. This table reveals a few interesting facts about the economic calculations. Before performing these calculations, there was an expectation that the “unmanned” system would provide significant savings on labor costs. However, this is not the main competitive advantage. The majority of the savings in the proposed system are due to the higher field efficiency. This higher efficiency leads to less time in the field, providing lower overall maintenance costs, lower fuel costs, and lower lubrication costs.

It is important to note that Table 4 refers to one very specific situation, the hypothetical 640 acre farm discussed in section 4.3.1. Total costs vary largely on the number of acres harvested, and larger acreages lead to higher costs, with total maintenance costs becoming significant as annual machine hours increase.

This model is valid for a wide range of ground speeds, yields, field sizes and other harvest parameters. The model is no longer valid when the machine hours fall outside the 300 to 3000 hour range specified in Table 2.

Table 4: Total Cost of Ownership

Total Costs												
Fixed Costs												
	Proposed				Conventional				Autonomous Conventional			
	Per acre	Per hour	Annual	Lifetime Total	Per acre	Per hour	Annual	Lifetime Total	Per acre	Per hour	Annual	Lifetime Total
Interest	$6.31	$51.63	$4,038.79	$40,387.89	$6.48	$43.87	$4,146.49	$41,464.90	$7.32	$49.57	$4,685.00	$46,849.95
Depreciation	$49.71	$406.76	$31,817.43	$318,174.33	$52.04	$352.35	$33,304.77	$333,047.72	$56.22	$380.63	$35,977.85	$359,778.53
Insurance	$2.93	$23.97	$1,875.00	$18,750.00	$3.01	$20.37	$1,925.00	$19,250.00	$3.40	$23.01	$2,175.00	$21,750.00
Housing	$0.81	$6.65	$520.31	$5,203.13	$0.94	$6.36	$601.25	$6,012.50	$0.94	$6.36	$601.25	$6,012.50
Subtotal	**$59.77**	**$489.01**	**$38,251.53**	**$382,515.34**	**$62.46**	**$422.94**	**$39,977.51**	**$399,775.12**	**$67.87**	**$459.57**	**$43,439.10**	**$434,390.98**
Varible Costs												
	Proposed				Conventional				Autonomous Conventional			
	Per acre	Per hour	Annual	Lifetime Total	Per acre	Per hour	Annual	Lifetime Total	Per acre	Per hour	Annual	Lifetime Total
Maintenance	$1.30	$10.62	$830.56	$8,305.56	$2.08	$14.06	$1,329.10	$13,290.98	$0.70	$7.45	$450.76	$4,507.62
Fuel	$4.69	$38.41	$3,004.18	$45,386.71	$7.38	$49.96	$4,722.25	$71,343.15	$5.36	$56.64	$5,180.53	$51,805.32
Lubrication	$0.70	$5.76	$450.63	$6,808.01	$1.11	$7.49	$708.34	$10,701.47	$0.80	$8.50	$514.35	$7,770.80
Labor	$2.11	$15.00	$1,349.33	$13,493.33	$2.10	$12.35	$1,342.45	$13,424.49	$1.63	$15.00	$1,044.38	$10,443.76
Subtotal	**$8.80**	**$69.78**	**$5,634.69**	**$73,993.61**	**$12.66**	**$83.86**	**$8,102.13**	**$108,760.09**	**$8.50**	**$87.58**	**$7,190.02**	**$74,527.49**
Total	**$68.57**	**$558.80**	**$43,886.23**	**$456,508.95**	**$75.12**	**$506.81**	**$48,079.65**	**$508,535.20**	**$76.37**	**$547.14**	**$50,629.12**	**$508,918.48**

4.4 Sensitivity Analysis

It is impossible to know the exact costs for producing the harvester or the exact costs paid by the farmer. A sensitivity analysis ensures that the conclusions drawn from this thesis are valid across a range of values. Several important sources of variability include total purchase price, maintenance, and field efficiency. For this analysis, comparisons will be provided between the proposed system and a conventional machine for brevity's sake.

Purchase price variability may come from several sources. It is difficult to estimate the final cost for the system when produced at scale. Comparisons can be drawn to similar existing equipment, but there are no widely used implements that have the proposed harvester's small size and mechanical complexity. With all other factors the same, increasing an individual harvester cost to $141,864 will increase the cost of the total system to greater than a conventional system. This is a total cost of $425,593.73, or $40,593.73 greater than the conventional system.

Maintenance costs are based on the results of survey data, but maintenance costs have high variability. Maintenance costs are expected to vary by ±25%, a difference of $2,076 for the life of the system. This is a roughly 4% of the overall difference between the two systems.

Field efficiency estimates are another source of uncertainty in the cost calculations. Field efficiency was assumed to be 90% for the proposed system. This is an estimate based on research in the area of agricultural path planning, but could vary considerably in the final product. With all other factors held constant, field efficiency would have to be lowered to 63% for the proposed system for the costs to increase $52,026 to equal the lifetime costs of the conventional system. If the field efficiency of the proposed system is lowered to 85%, the lifetime costs are increased by $6,869.12.

4.5 Smallest Economically Viable Farm

Decreasing equipment size provides a unique opportunity to examine the effects of smaller equipment sizes on small farms. New farm equipment is oftentimes far more expensive than a small farm can handle. The only options available to small farms are to purchase used equipment or to hire custom harvesting. Purchasing used equipment can often include hefty maintenance costs because the harvester has already accrued machine hours. Decreasing the size and cost of an individual machine makes new equipment purchases viable for smaller farmers. In order to quantify this effect, the harvested acreage needed to bring costs of ownership for one proposed combine and one conventional combine will be examined against the cost of hiring a custom harvesting operation.

It is important to note that there are several factors that farmers consider when comparing custom harvesting to owning equipment. With a custom harvester, the farmer has less control over harvest quality, harvest timeliness, and custom harvesters may not be available in a famer’s area. However, in order to make a comparison for this analysis, only the economics will be considered. For this analysis, a custom harvester rate of $40.00 per acre will be assumed.

In order for a farmer to have a per-acre cost of less than $40.00 per hour with one proposed machine, they must harvest 461 acres. For a conventional harvester, the harvested acres must exceed 2000 to bring the per-acre cost below $40.00 per acre. This result allows one of the proposed harvesters to economically harvest farms smaller than the median farm size. The smallest economically viable farm for a conventional harvester is far larger than the median farm size. This can be explained by a few factors. First, farmers frequently do custom work for friends and neighbors, helping to distribute the costs of the equipment. Harvesters are also often used for more than one crop, so a farm’s wheat, barley, and corn acreage would all be harvested by one machine. Most importantly, farms of smaller size frequently buy used equipment. Secondary, tertiary, and quaternary sales are an important part of the agricultural equipment market, both for equipment manufacturers and farmers. By buying used equipment, farmers face far lower depreciation and finance costs, but must pay higher maintenance and repair costs. It is not uncommon to see farmers using 30, 40, or even 50-year-old equipment, which allows these farmers to operate with far lower machinery costs, making their smaller farms more viable.

Chapter 5. Autonomous System Conceptual Design

This chapter presents the conceptual design and justification for the proposed smaller autonomous harvester. It covers both the basic mechanical and software concepts, as well as calculations necessary to develop an understanding of the economics of harvest, such as power requirements. This information is presented as a supplement to the economic analysis, to provide a better understanding of the total cost of ownership.

Design of a novel platform for any purpose is a process fraught with decisions about function and form. Designing and building a completely new system is outside the scope of this thesis, as a complete system would cost hundreds of thousands of dollars. Because the focus of this work is on the economic feasibility of this kind of system, a realistic conceptual design will be presented with supporting documentation to validate performance claims. A detailed design, with dimensioned drawings, supplier part numbers, and a kinematic analysis is neither feasible nor helpful for an economic discussion. The economic analysis presented in section Chapter 4 set the financial design constraints, and the following section discusses the functional requirements. The following section will discuss the design of small-scale autonomous harvesters at a high level.

There are two important and distinct aspects of designing any autonomous system: hardware and software. For this system, the hardware is simply a scaled version of existing technology. The software, however, is a new application for existing information, and essential to properly understanding the details of field efficiency calculations.

5.1 Platform Design

Design of the harvester platform is a scaling of existing harvesters. The basic design goal is to reduce the combine size to roughly one third of existing combines, but not every subsystem on a combine will scale linearly. Reaping, threshing, and separating subsystems have dimensions set by crop requirements, but other systems such as the drivetrain and bulk tank can be significantly reduced in size. Decreasing size will decrease power requirements, fuel requirements and provide other advantages.

5.1.1. Existing Small Scale Harvesters

When exploring small-scale harvesters, it is informative to look at existing equipment to develop an understanding of current solutions and set realistic design benchmarks. Small harvesters exist, used mainly for research plots, but they haven’t been used in autonomous applications. Adapting them for production harvest operations would require basic modifications to the mechanics and significant alteration to the control systems to allow for autonomous control. An example of a research plot combine is shown below in Figure 15. These combines are much smaller than conventional equipment, and approximate the design proposed for an autonomous system.

Figure 15: Research Plot Combine(Almaco 2013)

The pictured research combine is, with very limited differences, a scaled down version of a conventional combine. The drivetrain, reaping, threshing, and separating are all performed in the same manner. The only differences are in the bulk collection, because these combines are designed to return small samples to scientists, and as such have specialized equipment to perform that function. This research combine has a two person cab, with one serving as the operator and one collecting samples.

Research combines fill a very small niche in the harvester market. These combines collect small samples from agricultural experiments. These experimental plots may have hundreds of replications, which could be as small as eight feet on a side. These experimental combines are designed to harvest these individual plots, and have the ability to completely clear the system between plots to preserve the integrity of the collected samples. This is a tiny market, mostly limited to agricultural research institutes and seed companies. Without the advantage of economies of scale, this equipment becomes expensive. The cost for these research combines is roughly equal to the conventional equipment three times larger.

This research combine will be used as a starting point for the conceptual design. The proposed system will be similar in scale, but will process crop at a higher rate, necessitating several design changes. Discussion of the design will begin with traction and powertrain design, and will then discuss the reaping, threshing, and separating subsystems.

Starting a design from scratch provides the opportunity to craft a system with more consideration given for automation. Without a human operator cabs, air conditioning, radios, refrigerators, and other luxuries designed to ease the work of a long harvest season are irrelevant, saving money and space. Designing a system without a cab also frees up space in the front of the harvester to place sensors or adjust the layout of the harvester. Figure 16 and Figure 17 give an example of the design differences available when removing the cab of a combine. Figure 16 is a John Deere 9500 self-propelled combine, while Figure 17 shows a John Deere 9501 pull behind combine. While the pull behind lacks an engine to power the harvesting equipment, there is a clear size and layout difference available when there is no longer a need for an operator on board. Eliminating the cab and the need for an engine makes the system far more compact. On the proposed system, eliminating the cab frees more space in the forward part of the machine, and allows for a shorter length and shorter height.

Figure 16: John Deere 9500(William Kent Inc. 2010)

Figure 17: John Deere 9501("The Combine Forum" 2009)

A morphological chart detailing the sub-functions and possible solutions is shown below in Table 5. Options exist for nearly every sub-function, and a detailed description of each decision will be provided in later sections. The solutions represented here are common to combines, larger agricultural equipment, or applied autonomy solutions.

Table 5: Morphological chart for a harvest process

<table>
<tr><th></th><th></th><th colspan="4">Solutions</th></tr>
<tr><td rowspan="8">Sub Functions</td><td>Drive</td><td colspan="2">Differential</td><td colspan="2">Reverse Ackerman</td></tr>
<tr><td>Power</td><td colspan="2">Diesel</td><td colspan="2">Gasoline</td></tr>
<tr><td>Reaping</td><td colspan="4">Snapping Rollers</td></tr>
<tr><td>Threshing</td><td colspan="2">Tangential</td><td colspan="2">Axial</td></tr>
<tr><td>Seperating</td><td colspan="2">Straw Walker</td><td colspan="2">Axial</td></tr>
<tr><td>External Sensing</td><td>LIDAR</td><td>RADAR</td><td>Camera</td><td>GPS</td></tr>
<tr><td>Internal Sensing</td><td colspan="2">Grain Loss</td><td colspan="2">Speed Sensors</td></tr>
<tr><td>Computing</td><td colspan="2">Server</td><td colspan="2">PC</td></tr>
</table>

5.1.2. Power and Drivetrain

The powertrain and traction of the autonomous system will be different from most other grain harvesters. This system will use a hydrostatic differential drive, with caster wheels in the rear. Conventional combines use rear Ackermann steering, but differential drive provides advantages in controlling and path planning. The motion modeling and control is simpler, and the ability to pivot about the center of the axle simplifies path planning. While differential drive is not currently used in grain harvest, the technology is common in self-propelled windrowers. It has also been used in autonomous harvest systems, specifically Demeter, where the use of differential drive allowed the windrower to make point turns, simplifying the path planning and following(Pilarski et al. 1999). Figure 18 shows Demeter, with the caster wheels clearly visible in the rear of the windrower.

Figure 18: Demeter Automated Windrower(National Robotics Engineering Center 2013)

Hydrostatic drive is a standard method of transmitting motive power from the engine to the wheels, and an appropriate solution for automation. A hydrostatic drivetrain serves several functions in this automated system. Fluid drives allow for infinite variability in the drive speed, which allows for any turn radii needed by the control software. This variable ground speed also allows the machine to match crop throughput (controlled by groundspeed) to the system capacity. In areas with high yield, slow ground speeds are needed to ensure that the system is not overwhelmed by the high grain flow. In lower yield areas, ground speed can be increased to increase the crop throughput, maintaining a constant grain flow.

A hydrostatic drive serves to decouple the engine speed from the ground speed. Heavy-duty diesel engines, like the kind used in agricultural equipment, are optimized to run at one speed. On tractors, this provides a constant speed output to any implement attached via PTO shaft, which is necessary for proper operation. Tractors have transmissions with a large number of gears to match the speed of the tractor to the speed of the PTO-driven implement. On a combine, the engine is directly connected to the reaping, threshing, and separating subsystems which require a constant engine speed. A hydrostatic drive allows the engine to operate at its set point and the wheels to match the crop throughput to the machine capacity by adjusting groundspeed, as discussed above, without constant gear shifting.

The benchmark for the drivetrain design is 5 miles per hour. This speed is the high end of the typical combine operating range(American Society of Agricultural and Biological Engineers 2011), allowing the proposed harvester to maintain a competitive acres per hour rate. This speed coupled with a two-row header using 30 inch row spacing will harvest 3.03 acres per hour.

The drivetrain will be powered by a heavy-duty diesel engine, such as the John Deere 4045 industrial engine shown in Figure 19. A heavy-duty diesel provides several advantages over alternative solutions. First among them is the ease into which it integrates with the other agricultural equipment found on modern farms. With very limited exceptions, most equipment is designed for use with off-road diesel fuel. By using diesel fuel, in-field refueling is simplified, and can be done using the same tanks and pumps currently used to refill equipment.

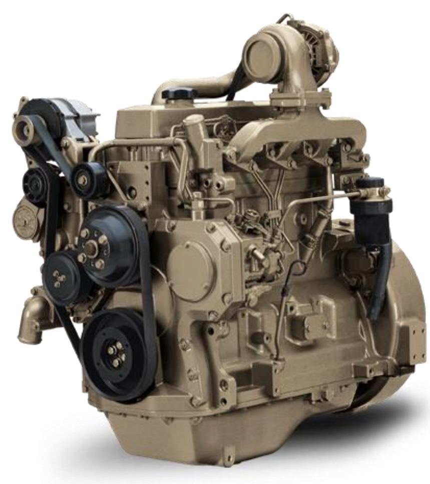


Figure 19: Heavy duty diesel engine(John Deere 2013)

Industrial and agricultural diesel engines are optimized to run at one speed. This rated speed provides one set point that can be used to design the rest of the system, which is important for designing moving components throughout the harvest equipment. These engines are also designed to produce their rated horsepower at the rated engine speed continuously. The components of industrial diesel engines are designed for extremely high fatigue cycles and can produce their rated horsepower for thousands of hours before major overhauls are needed. The engine used in this system would include a turbocharger, both to increase the rated horsepower relative for a given engine weight and to improve fuel efficiency. These diesel engine traits are ideal for the proposed autonomous system.

The alternate solutions for motive power are gasoline engines or electric motors. Heavy-duty gasoline engines are very heavy, and far less fuel efficient than diesel engines. The advantages of electric motors, namely high starting torque and infinitely variable speeds, are matched in the proposed system by hydrostatic drives. The batteries needed to power an all-electric system are extremely heavy, and long recharging cycles are unacceptable during harvest time.

5.1.3. Reaping

The harvesting equipment attached to the base platform will be similar to that used by conventional combines. The proposed system will use two row headers with snapping rollers, much like what is found on conventional combines, but used on a much smaller head. The choice to use two rows is based on machine capacity. A one-row harvester would be easy to build, but increasing the number of rows harvested better utilizes the resources available. Components on each machine that are independent of size, such as computing, sensing, and actuation hardware, have a cost that is largely independent of machine size. For this system, the goal is to explore the economic advantages of a smaller, more mobile system, and two rows is more effective than one in utilizing the available power and threshing capacity. At the opposite end of the spectrum, reaping too many rows will overwhelm the threshing capacity of the combine.

The head proposed for this autonomous system is simply a two-row version of conventional systems. As discussed in section 3.4, snapping rollers grab the corn stalk between two fluted rollers and pull it through a set of plates that snap the ear off of the stalk. Theoretically, this should leave the stalk on the ground below the header while the ear is moved by a gathering chain to the thresher. However, stalks are often pulled into the thresher along with the corn. These stalks, in addition to the cobs, husks, and other plant matter passed through the combine is known as “material other than grain,” or MOG. The MOG is an important factor in the effectiveness of the thresher, as excessive MOG reduces the ability to knock the kernels off of the cob, and reduces the ability of the grain to fall through the MOG in the separator. Because the system used to reap the corn is the same as conventional systems, statistics for grain to MOG ratios from conventional combines are also applicable to the proposed system. In tests of conventional equipment, an MOG to grain ratio of 20-30 percent is typical. In this analysis, a MOG/grain ratio of 25% will be used(Hill 2012).

5.1.4. Threshing

Threshing of the grain will be performed using an axial threshing cylinder, much like a conventional system. An axial rotor will be used because of space constraints, and because of superior threshing characteristics, as shown below in Figure 20. The exception to the generally superior performance characteristics of the axial rotor is an increased power requirement. This is an acceptable tradeoff for this system because harvest efficiency is critical to success of the machine, while marginal power increases are acceptable and can be provided for a reasonable cost. Power to drive the threshing cylinder will be supplied via a hydrostatic motor.

Compared to a tangential system, an axial system provides several advantages. Most importantly for this application, an axial threshing and separating system is a more compact physical package than conventional tangential cylinders and straw walkers. An axial rotor is directly connected to an axial separator, reducing the number of moving parts, and simplifying maintenance. A reduction in footprint will reduce the overall size of the harvester, reducing weight and cost. Tangential threshing cylinders are placed across the width of a harvester, parallel with the axles. In this configuration, machine capacity is determined by the diameter width of the cylinder, necessitating an increase in machine width to increase capacity. In an axial system, the threshing and separating takes place perpendicular to the axles, allowing for a more compact layout. The capacity is determined by cylinder diameter, and cylinder length determines the effectiveness of the separating system. This configuration provides superior threshing and separating characteristics, and makes the system more space efficient, improving the economics of transportation and storage.

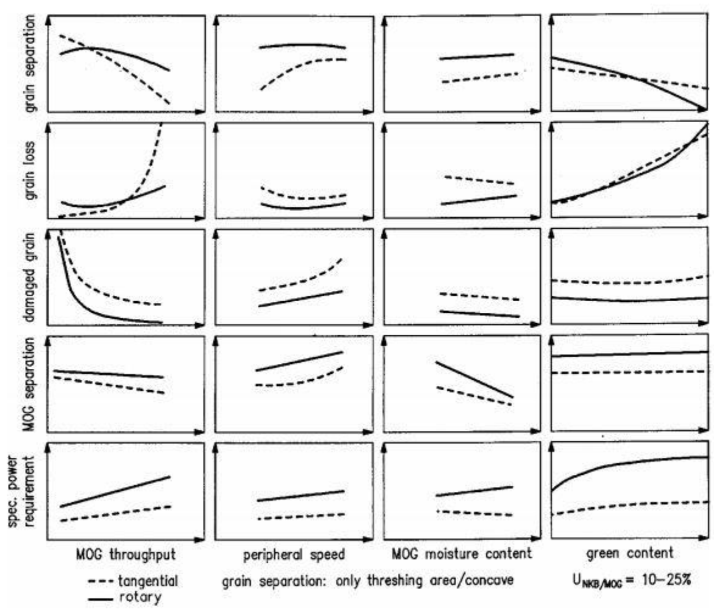


Figure 20: Comparison of Tangential vs. Rotary Threshing(Stout et al. 1999)

The threshing cylinder will be driven using a hydraulic motor. Much like the hydrostatic system driving the wheels, this serves to decouple the cylinder speed from engine speed. Appropriate cylinder speed is an important factor in successful threshing. If cylinder speed is too low, the kernels will not be separated from the cob, and grain will be passed through the combine without being harvested. If the cylinder speed is too high, the individual kernels will be damaged, and blown out of the combine with the chaff in the separating subsystem. Hydrostatic drives also help isolate the engine from the variable power requirements of a threshing cylinder. Inconsistent material flow rates through the system due to variation in crop yields, high weed populations, or changes in ground speed all affect how much power the threshing cylinder requires. While the rate of crop material fed into the combine is primarily controlled by adjusting ground speed, the ability to maintain threshing cylinder rotation speed via an increase in hydrostatic pressure helps maintain uniform threshing. A hydrostatic drive, coupled with sensing and control, will allow the threshing system to run at the appropriate speed and ensure a consistent harvest.

5.1.5. Separating

Separating grain from the stalks and cobs is performed by an axial rotary separator. Unlike early straw walker systems, rotary separators use centrifugal force instead of gravity to separate heavier grains from the lighter straw. This provides several advantages, including more complete separation, smaller footprint, and simpler mechanical systems, but comes at the cost of higher power requirements. After falling from the rotary separator, the grain will be separated using chaffer tables and a hydraulically powered blower. Both of the systems are functionally the same as conventional combines.

After separation, the grain goes to a bulk tank. This serves as temporary storage while the equipment is operating in the field. Once the bulk tank is full, it will then be offloaded into a grain cart. Appropriate sizing of the bulk tank is important for this application. If the tank is too small, and the combine will waste time driving to and from the grain cart mid-row. If the tank is too large, the weight of the grain will necessitate a higher power drivetrain and make vehicle handling unwieldy. For this application, the bulk tank size is designed to be roughly the amount of grain needed to make 2 passes through the field. In most applications, a grain cart or tractor-trailer will park next to the field entrance, and two passes will allow the harvester to offload when closest to the field entrance without having to make unnecessary stops. The equation for calculating the grain tank size is shown in equation (5.1).

$$Grain\ Volume = Swath\ Width * 2 * Field\ length * Yield \tag{5.1}$$

For this calculation, the field is assumed to be a quarter section, which is a quarter mile by quarter mile square. Swath width is 60 inches, or 2 rows on 30 inch spacing. The yield is conservatively estimated at 250 bushels per acre. This is a very conservative estimate, as the highest average yield for Iowa rarely approaches 200 bushels per acre(Brien 2013), but in-field variability means local yields may approach this value. This result of this calculation is 75 bushels of grain for 2 passes through a field, which is a reasonable value for a combine of this size.

5.1.6. Sensing

The sensing requirements of any autonomous mobile robot are not trivial, but the sensing needed to operate a combine at settings designed to maximize the harvest yield are even greater. The sensing requirements for this system can be roughly broken into two categories: environmental sensors and internal sensors. Environmental sensors will localize the robot and maintain machine and bystander safety. Internal sensors will monitor the harvest parameters to keep the machine operating at its maximum capacity.

Environmental sensors serve two functions: localizing the harvester within the field, and protecting the machine and bystanders. Localizing is a critical function for path planning and recording the progress of the machine through the field. It also will be used to accurately locate the machine between the rows. Protecting the machine and bystanders is necessary for the safety of both the people operating the system, the safety of the machine itself, and for the fields and surrounding objects.

GPS is the most widely used localization sensor for outdoor environments. The standard GPS signal is, on average, accurate to 4 to 5 meters(William J Hughes Technical Center 2013). This is far too inaccurate for use in agriculture, where typical pass-to-pass accuracy must be 6 inches or less. For corn harvest, the head must be roughly centered on the rows, which are commonly spaced 30 inches apart. Some offset can be tolerated, but an accuracy of a few inches is needed to effectively reap the corn. Some error correction can be done manually, using feelers to center the machine on the row, but correction GPS error must be performed for acceptable machine performance.

Several methods can be used to improve the accuracy of a GPS system. Each method provides a corrective signal to correct positional error. Some examples of these kinds of systems include differential GPS (dGPS), real time kinematic (RTK) navigation, and proprietary systems such as John Deere StarFire. Each of these systems calculate a correction to the received GPS signal to improve accuracy. These corrections can provide up to centimeter-level accuracy, which is sufficiently accurate for the proposed autonomous system.

Environmental systems must also detect objects around the equipment. LIDAR and radar systems can both be used for range and object detection. While LIDAR systems are widely used in robotic systems and provide excellent accuracy and ranging distance, their performance is significantly degraded by dust. Radar systems are much more dust tolerant and provide very good range information. Because a field during harvest is frequently a high-dust environment, several radar sensors will be used to acquire ranging data.

Using computer vision for sensing is a widely utilized technology. The most successful modern systems are implemented in highly controlled environments, used in roles such as part inspection in factories. In these situations the environment can be tightly controlled, with consistent lighting and placement of objects to be inspected. Computer vision has long been applied to autonomous systems, with varying degrees of success. In this application, there exists enough structure to apply computer vision with reasonable expectation for success. Previous robotics project have used computer vision to control robotic systems in row crops, namely the Demeter system(Pilarski et al. 1999). In this system, knowledge of the structure of the environment simplifies the software needed for control. In a corn crop, the combine must follow the corn rows, which provides structure to the environment for machine guidance.

Multiple cameras will be used together to monitor several areas around the combine. Camera placement is an important consideration in both software development and operation. Front and rear cameras are important for object detection while driving. Higher mounting points provide the ability to see over close, low obstacles such as high grass. Another important camera mounting location provides a view of the spout that unloads grain from the combine to the grain cart. This will be used when offloading to make sure that grain is evenly distributed on the cart, which maximizes the capacity of the existing equipment.

Computer vision will also be used for safety systems. Farming is a dangerous profession, with 2010 fatality rate of 26.1 deaths per 100,000 workers (476 deaths total), and 23% of those fatalities involved machinery(Centers for Disease Control and Prevention 2011). Agricultural equipment is dangerous because of its large size, rotating shafts, and the high levels of interaction between operators and equipment. An autonomous system will have less direct interaction with an operator, but precautions need to be taken to avoid striking a worker or other object in the field. Computer vision gives the ability to see and identify obstacles, detect humans, and otherwise identify hazardous situations.

The autonomous system's internal sensors and actuation serve as a replacement for a skilled combine operator. There are several operator adjustable settings on a modern combine: concave clearance, sieve openings, blower speed, rotor speed, and ground speed along with several other parameters all factor into the effectiveness of the harvest system. A skilled operator knows how to adjust these settings to maximize yield as well as maintain a ground speed that utilizes the capacity of the machine. Without an operator, these functions must be replaced by sensing and actuation.

The end goal of sensing the machine parameters is to maximize the harvest yield. Loss of grain can occur in the threshing, separating, or cleaning stages and each has adjustments to minimize harvest loss. Grain fluoresces under UV light, and, using this property, it is possible to determine how much grain is exiting the rear of the combine with the MOG. This, combined with information on the quality of grain entering the bulk tank, is how adjustments to the various combine settings are determined.

Threshing problems, due to either over-threshing or under-threshing, can be corrected by adjusting cylinder speed to crop conditions. Several patents detail a closed loop system that senses grain conditions and adjusts the cylinder to either remove more grain from the cob or reduce kernel damage(Mailander, Krutz, and Huggins 1982)(Diekhans 2001)(Hoskinson et al. 2003). Threshing issues are detected by observing the grain and the cob. Ideally, proper threshing due to appropriate cylinder speeds result in whole kernels separated from the cob without excessive breakage to the cob. Under-threshing results in kernels left on the cob while over-threshing results in cracked kernels and broken cobs. By observing the grain entering the bulk tank and the MOG exiting the combine, the correct cylinder speed can be determined.

Two points of adjustability exist in the cleaning system: the chaffer and sieve openings and the fan speed. If the chaffer and sieve are too open, crop debris will be allowed in the bulk tank. If these are too narrow, grain will be returned to the threshing cylinder for more threshing, over-threshing the already separated kernels and damaging the crop. If the fan speed is too low, the detritus from the stalk and cobs will not be blown off the shoe. If the fan speed is too high, the grain will be blown out the rear of the combine.

The current method for determining the appropriate settings for a combine loosely follow the guidelines above. Basic settings are usually given in a chart for each crop, and these are the baseline settings. From there, an operator will observe the grain entering the bulk tank for excess foreign debris and cracked kernels. The threshing cylinder speed will then be adjusted accordingly. The separating system is then adjusted by observing the MOG over the chaffers. The top sieve is adjusted to let all threshed grain and unthreshed grain still attached to cobs/straw through, while the bottom sieve is adjusted to allow only threshed grain through. Fan speed is set to the highest recommended speed and reduced if grain is being blown out of the combine.

The autonomous system will behave in much the same manner, although with much more accurate feedback. Grain loss sensors will provide much faster feedback for the system, and allow more precise feedback on the effects of changing machine settings. In a conventional system, setting may be adjusted once per day or less. On an autonomous system, there are gains to be made in continuously adjusting the machine parameters to harvest conditions. Frequent rapid adjustments are unnecessary, so any sensor/actuation feedback loops will have very low gains.

5.1.7. Computing

It is difficult to determine computing requirements for a conceptual system without full knowledge and testing of the software that will run on the computing hardware. Examining other autonomous systems will similar sensing and automation requirements will provide and estimation of the system's computing requirements. The DARPA Grand Challenge and DARPA Urban Challenge are two highly documented autonomous systems competitions that have inspired vehicles with similar sensing and computing requirements. Teams used several different solutions for computing, ranging from blade servers to a single laptop(Leonard et al. 2007)(Mason et al. 2006). This is the scale of computing expected for this system, with a high priority placed on reliability. The autonomous systems in the DARPA challenges and the proposed harvesters are very similar. Both use a large number of various sensors, calculate paths, follow navigation rules, and avoid obstacles. Using these vehicles as a guide, the computing system for harvester can be estimated.

For design purposes, a server-class system will be assumed. A multi-core CPU, large RAM capacities, and the ability to communicate via USB, Ethernet and various serial protocols make this type of computer an attractive solution. It also represents a very conservative option for computer, because it may be possible to run everything on a more typical computer system. However, using a server as the design basis provides a level of future-proofing and provides significant computing headroom.

It is important to have ruggedized computing for systems operating in agricultural equipment. Unlike most vehicles, and especially vehicles designed for off-road use, agricultural equipment in general and the proposed harvest in particular have no suspension systems. This leads to a high vibration environment. The proposed harvester may also operate in high dust and high temperature environments, making cooling an important consideration. Many options exist for passive cooling, and computing solutions have been developed that can operate in these conditions.

5.2 Software Design

Software represents a possibility of large productivity gains in the operation of harvest equipment. This harvester will utilize a semi-autonomous design requiring limited human input for unfamiliar situations. This method represents an advancement in current technology and a realistic solution that maintains human control in dangerous or unfamiliar territory. When operating normally in an unobstructed field, the harvester will have full control in order to optimize the harvest.

Software algorithms for harvest paths have been studied at length, and several options exist to efficiently remove the crop in the field. In the software applied to this problem, improving field efficiency is the ultimate goal. Field efficiency is the ratio of time spent in the field to the time spent harvesting. Current harvesting methods have a field efficiency of between 65% and 80%, with 70% being a typical value(American Society of Agricultural and Biological Engineers 2011). Thirty percent of the time a machine spends in a field is spent on something other than harvest, whether it's personal time for the operator, time spent turning the machine at the end of a row, or time spent offloading grain into a grain cart. Moving to a fully autonomous system removes the operator-induced downtime, and allows for a motion plan that maximizes the amount of time harvesting grain.

Increasing field efficiency represents a concrete increase in productivity for an agricultural producer. Harvesting more grain in less time or with fewer resources is one of the greatest benefits to using autonomous equipment, and is an important economic advantage over a conventional system. The efficiency gains due to path planning software that maximize harvest efficiency have no costs associated with them outside development costs. A conventional combine can make efficiency gains by better training of the operator, but getting more work from the operator increases fatigue. Software development will be focused on maximizing efficiency, with a goal of 90-95% field efficiency. Increasing efficiency from 70% to 95% would mean three more hours of harvesting in a twelve-hour day. Production gains such as that make autonomous technology much more economically justifiable, and would greatly influence the purchasing decisions of a farmer.

Utilizing software optimized for production gains has significant impact on field efficiency. One method reduced overhead time by an average of 29%(Oksanen and Visala 2009). By developing code that takes advantage of the differential steering characteristics and maximizing the time spent harvesting grain, the efficiency can be greatly increased.

Safety software is also essential to operation of an autonomous system. It is the safety system that will integrate most of the environmental sensors, as the purpose of these sensors is to protect the people from the robot and the robot from obstacles in the environment. The highest priority in any safety system for this robot is protecting human life. The safety of the operators and bystanders is more important than machine preservation or harvest operations. Loss of human life is unacceptable from a moral perspective, but also would render any autonomous system unviable, and would set the field of autonomous robotics back significantly based on reputation alone. Because of this, sophisticated and redundant systems will be used to ensure that humans can be identified and avoided.

Computer vision and machine learning software can be used to autonomously detect humans and act to protect them(Gandhi and Trivedi 2008). Any system used in an unstructured environment such as a field must be robust against challenges such as occluded bodies. This is an area of current research, and the ability to detect humans and other obstacles will continue to improve. Machine learning has been applied to areas of research throughout agriculture, with significant research done in determining areas of safe operation and classifying the environment surrounding a vehicle(Dima, Vandapel, and Hebert 1992)(Wellington, Courville, and Stentz).

As discussed in Section 4.3.2.2.4, this system will utilize the "human oracle" model of human supervision. In this model, if the system encounters a situation where it cannot navigate around an obstacle, does not have classification information for the current system, or otherwise is unable to proceed autonomously, it queries a human operator for assistance. This allows the human to supervise several robots at once, and also allows a safe failure mode for software that encounters an unfamiliar situation. This model also provides a fantastic environment to build a trained classifier for machine learning, by using the human guidance to manually train machine learning algorithms when they encounter situations for which they do not have a classification.

Communicating with the operator will require wireless transmission, which introduces the issue of bandwidth limitations. Combine machine health can be monitored using data for each subsystem such as RPM or hydraulic motor load, as is currently communicated to the operator. John Deere's GreenStar 3 2630 harvest monitor records 16 pieces of information for row crop harvest(John Deere 2013b). The largest source of data usage would be video transmissions required for tele-operation. Communication design should focus on limiting unneeded data transmission while still providing an awareness of machine conditions. 3G data rates vary, but can be expected to be between 348kbit/s and 2Mbit/s. Through judicious use of resources, it may be possible to transmit enough video to give operators full awareness of the harvester surroundings. However, an ad-hoc network may be more appropriate to guarantee higher data throughput.

5.3 Power Requirements

Determining power requirements for the proposed system is an important tool in selecting an engine size and selecting appropriate sizes for other components of the combine. It will also provide important information for calculating fuel consumption and other economic metrics. Power requirements can be estimated from published data and by using statistics from similar systems. The power consumption will be calculated by subsystem with drivetrain, reaping, threshing, separating, and electronics comprising the main powered systems.

5.3.1. Powertrain

Drivetrain power consumption can be estimated by calculating rolling resistance and gradient losses and multiplying by ground speed, as shown in equations (5.2), (5.3), and (5.4). Rolling resistance is a function of the weight of the vehicle and f_{rr}, the coefficient of rolling resistance. For the purposes of this calculation, f_{rr} is estimated to be 0.078(Máthé 2012). Gradient loss is a function of the weight of the vehicle and slope. The maximum recommended slope for cultivation is 15%(Clemson University 1988), an angle of roughly 8.5 degrees.

Tractive Power $$P_t = P_{rr} + P_g \quad (5.2)$$

Rolling Loss $$P_{rr} = m * g * f_{rr} * v * \cos\alpha \tag{5.3}$$

Gradient Loss $$P_g = m * g * v * \sin\alpha \tag{5.4}$$

For these calculations, the vehicle weight is estimated to be 10,000 pounds, in addition to 75 bushels of 56 pounds per bushel corn for a total vehicle weight of approximately 15,000 pounds. When calculating the power draw, the forward speed is set at 5 miles per hour. When driving a vehicle with these specifications up a 15% slope, the rolling loss is 15 horsepower, and the gradient loss is 30 horsepower.

Powertrain estimations frequently include aerodynamic and inertial but for the purposes of these calculations, these factors are considered negligible. At 5 mph, the aerodynamic forces are minimal. Inertial losses will factor heavily into starting power requirements, but the vehicle will spend most of its operation at steady state. Rolling loss and gradient loss dominate total tractive power calculations, and in this application aerodynamic and inertial losses represent a negligible portion of the overall power consumption.

The drivetrain will utilize a hydrostatic drive, so the mechanical efficiency of this power transmission system must be considered when calculating power draw. For a hydrostatic drive system, efficiencies of 80% are common(Cundiff 2001). Therefore, a 56.25 engine horsepower are required to develop 45 wheel horsepower after being transmitted through a hydrostatic drive.

5.3.2. Reaping

Very little research exists on the power requirements for reaping. According to Hunt (Hunt 2001), reaping the header mechanism has a constant no-load power draw, independent of ground speed. The tested header mechanism was a 3 row, 30 inch spacing, hydrostatically driven head, and consumed 3kW across a wide range of ground speeds. Because the proposed harvester has a two row head, no-load power consumption is estimated to be two thirds of the equipment used for testing in the Hunt literature, giving a power consumption of 2kW, or 2.68 horsepower.

Very little published research exists for determining the loaded power draw of a combine header. Published research on this process used modeling and simulation to determine that roughly 2000 joules of energy is expended for snapping rollers to reap one stalk of corn(Ni et al. 2012). Using an estimated plant spacing of 6 inches and a forward speed of 5 miles per hour, the power draw is calculated to be 1.14 horsepower per row, or 2.29 horsepower total. Combining the no-load power draw with the estimated power consumption from the stalks, a total power draw is determined to be approximately 5 horsepower.

5.3.3. Threshing and Separating

In a harvester with an axial layout, the threshing and separating are performed on the same cylinder. Power calculations for this system will be performed together because these systems work as one unit with one power source. The power requirements for axial threshing have less published research available than tangential threshing. This is due to largely to the recent development of axial threshing technology and to the nature of the axial flow harvesting system. Threshing cylinders are commonly estimated to consume 40% of total harvester power, making the estimates for threshing and separating power consumption essential to an accurate overall power estimate.

Threshing power requirements are a function of the crop feed rate, and specific power requirements are calculated as a function of MOG processing rate. The MOG feed rate can be calculated using the estimated operating parameters and corn physiological data discussed in section 3.1. The equation for this calculation is shown in equation (5.5). Head width is in feet, ground speed is in feet per second, yield is in bushels per acre, and the constants of 56, 0.845, .4535, and 43560, represent pounds per bushel, MOG weight per pound of grain, kilograms per pound, and square feet per acre, respectively. The head width is 60 inches, or 2 30-inch spaced rows. The .25 constant used in this equation represents the effectiveness of the snapping rollers. As discussed in section 5.1.3 the snapping rollers should, in theory, remove ears from the stalk, and deposit the stalk on the ground while passing all ears into the thresher. In practice, stalks get passed into the thresher, at a MOG to grain ratio of .25(Prairie Agricultural Machinery Institute 2013). The ground speed is estimated to be 5 mph, as discussed below.

$$m_{\dot{MOG}} = \frac{Head\ Width * Ground\ Speed * Yield * 56 * .845 * .4536}{43560} * .25 \qquad (5.5)$$

Miu and Fellow calculated the specific process power for wheat threshing and separating to be approximately 7 kW/(kg/s) for 1.1 kg/s of MOG(Miu and Fellow 2001). Using data from the Colorado State extension service, corn harvest is estimated to consume 60% more power than wheat harvest(Colorado State University Extension Service). Power needed for a axial threshing of a specific crop harvest varies linearly with MOG feed rate(Miu and Fellow 2001). For the purposes of this analysis, this 60% power increase is assumed to be a linear relationship across the range of harvest speeds. This assumption is based on several factors: the mechanical principles of separation remain the same for each grain; the higher yield of corn crop necessitate hire MOG throughput; and required threshing power increases linearly with MOG feed rate(Miu and Fellow 2001). A 60% increase in specific power gives an estimated specific process power of 11.2kW/(kg/s), for a total of 12.54 kW or 16.84 horsepower. These numbers provide the process power, or power needed to separate the kernels from the cob. Idle power, or the power needed to spin the rotor under a no-load condition were also estimated from Miu and Fellow research(Miu and Fellow 2001). Idle power represents an additional 6.7 horsepower, for a total of 23.55 horsepower used in the threshing system.

For this calculation, the ground speed is assumed to be 5 mph. If the yield estimate of 250 bushels per acre is used, the power estimated calculated above gives a power draw of 23.55 horsepower. Using a more realistic average yield of 180 bushels per acre gives a total power draw of 18.88 horsepower. When designing a system for an environment as unstructured and varied as a cornfield, it is important to build a margin of safety into the design so that a harvester can handle high dynamic loads to the threshing system. Conventional systems often run at less than 50% engine loading, but the overhead capacity allows the threshing system to quickly return to the set cylinder speed(Hunt 2001).

As with drivetrain, power will be transmitted to the axial threshing and cylinder by means of a hydrostatic drive. In order to provide 23.55 horsepower at the threshing cylinder, 29.44 engine horsepower are required.

5.3.4. Grain Cleaning

The grain cleaning system of a combine typically consists of a series of actuated sieves and a fan or blower. This system loosens the crop material by both movement and airflow, allowing the heaver grain to fall through while blowing away lighter detritus like corncob pieces. Sizing for the cleaning sieves is based on crop throughput, and fan size is based on the needed airflow. Airflow requirements are determined by the terminal velocity of corn kernels and the terminal velocity of the cobs and stalks. Kernels have a much higher terminal velocity than the other material, so setting air velocity between the two terminal velocities allow the kernels to fall while blowing the chaff away. For corn, this velocity is between 26 and 42 feet per second(Uhl and Lamp 1966). Selecting a fan to achieve this velocity depends heavily on the cross sectional area of the cleaning shoe and the static pressure developed by the MOG mat on top of the chaffers. Without a detailed design, the best way to estimate the power requirement of this subsystem is by comparing power requirements of existing equipment. In the CIGR Handbook of Agricultural Engineering a combine using 27kW for threshing and separation uses 10kW for cleaning(Stout et al. 1999). Using this ratio, the 23.7 horsepower threshing cylinder will require 8.77 horsepower for the cleaning system. As with the drivetrain and threshing, this system will be powered by hydrostatic drives. After factoring in the 80% efficiency of this system, the total estimated power required for the cleaning system is 11.0 horsepower.

5.3.5. Electronics

Power requirements for electronics are a usually small compared to the overall power requirements for agricultural equipment. For a small harvester with a suite of sensors and computers, it is important to consider the power drawn by electronics. Without a detailed list of components, it is difficult calculate the power that will be drawn by the system. Power requirements will instead be estimated by comparison to other computing and sensing intensive autonomous systems.

The 2005 DARPA Grand Challenge provides a wide selection of vehicles and sensor designs useful in determining typical power usage. In these vehicles, a variety of stereo vision, LIDAR, radar, and computing systems were used for obstacle detection and path planning(Cremean et al. 2006; Mason et al. 2006; Leonard et al. 2007). These systems have architectures similar to a system that would be used in autonomous harvesting, making power comparisons valid between the two systems.

Power consumption in many of the vehicles used for the grand challenge were typically reported to be 2-3 kilowatts(Cremean et al. 2006; Mason et al. 2006; Leonard et al. 2007), with one group reporting use of a 6 kW alternator that vastly exceeded the power draw(Urmson et al. 2007). For the purposes of this analysis, power draw is assumed to be 4 kilowatts, or 5.37 horsepower. This is a conservative estimate which leaves headroom for other systems on the harvester that will use power generated by the alternator.

Calculating alternator efficiency is dependent on several factors, including load. Typical efficiencies can range from 55% to 80%(Bradfield). Because both the load and the engine speed are constant, it is possible to select an alternator that maximizes efficiency. The estimated efficiency for an alternator for this designed is assumed to be 75%, giving an engine power requirement of 7.16 horsepower.

5.3.6. Total Power Requirements

A general estimate for the total power requirement of the combine can be determined using the calculations performed in the above sections. Using estimated power requirements of 56.25 horsepower for the drivetrain, 5 horsepower for reaping, 29.44 horsepower for threshing, 11.0 horsepower for cleaning and 7.16 horsepower for electronics gives an overall draw of 108.85 horsepower. This total power draw does not include ancillary systems such as the grain unloader, internal conveyor systems, and other ancillary systems. However, the power requirements are either quite small, or intermittent. As discussed in section 5.3.3, the calculated power estimates are very conservative, and provide significant headroom for high dynamic power requirements. The calculated power requirements represent a worst-case scenario: harvesting 250 bushel/acre corn moving up a 15% slope and hauling a fully loaded grain tank at 5 mph. To estimate a more typical loading scenario, the power usage for a 3% slope and 180 bushel/acre yields scenario was calculated, resulting in a total power usage of 73.81 horsepower, which is 68% of the maximum load.

In the event that the designed headroom fails to meet the demands of the harvester, power requirements can also be adjusted on the fly by simply slowing down the machine. A skilled operator both listens for engine load and monitors engine speed through the use of a tachometer. If an operator senses that the engine is becoming heavily loaded, due to high weed populations, high yield, or steep terrain, he can reduce the power requirements of the system by decreasing ground speed. In an autonomous system, engine loading can be monitored in a similar way, and the ground speed can be controlled in the same fashion in order to maintain proper engine speed.

5.3.7. Fuel Consumption

After a calculation of power requirements, it is possible to estimate fuel consumption. Figure 21, taken from Wong(J. Y. Wong 2008), shows a typical engine specific fuel consumption curve for diesel engines. As discussed in section 5.3.6, the maximum engine capacity is 108.85 horsepower, but the typical loading is 73.81 horsepower, or 68% of the maximum. A typical set point for engine speed is 2000 RPM, giving a specific fuel consumption of .38 to .4 pounds of fuel per horsepower per hour. Using 73.81 horsepower, and given a diesel fuel density of 7.3 pounds per gallon, the specific fuel usage for this application is 4.06 gallons of fuel per hour of use. In a 12-hour operating period, these machines would use 48.67 gallons of fuel, so a 50-gallon fuel tank would be appropriate.

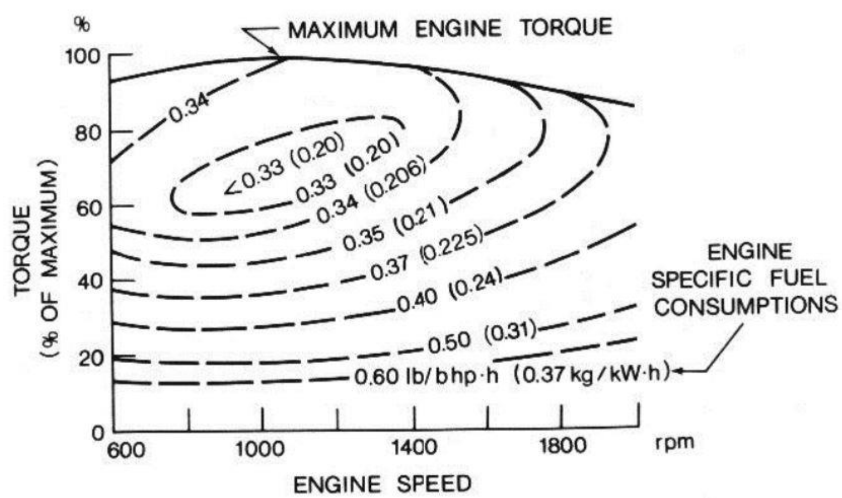


Figure 21: Engine Specific Fuel Consumption(J. Y. Wong 2008)

5.4 Size Requirements

Estimating the size requirements for this system is important for determine several costs of operation. Both storage costs and transportation costs are heavily dependent on the size of the vehicle. These expenses are better understood by developing basic size requirements.

5.4.1. Row Size

Several standard row spacings are used in corn crops, but the most typical spacing is 30 inches(National Agricultural Statistics Service 2012b). This spacing sets a maximum width for the system. In order to run in the field and not drive over unharvested rows, the harvester cannot be wider than the two harvested rows, plus the spacing to the left and right rows. This gives a maximum width of just under 120 inches, but a more realistic width of 90 inches, which is two row widths and 15 inches outside either end of the harvested rows. This width falls within the federal transportation width limit of 102 inches(US Department of Transportation Federal Highway Administration 2004).

Machine length is less constrained than machine width, but dimensions are still dictated by the harvest system. The goal length for this system is 18.5 feet. This figure is driven by transportation costs, as a single drop deck trailer has a deck length of 37 feet, allowing two harvesters to be transported by one tractor-trailer. As seen in Figure 22, grain separation asymptotically approaches 100%, but a length of between 1.2 and 2 meters (4 to 6.5 feet) provides adequate separation. The axial rotor is the main driver for machine size, and as such helps determine the overall length. Another important driver of machine length is the header, which protrudes 10 feet beyond the feeder housing(Case International 2013). The cones that separate the rows can be folded for transport, giving a transportation length of 7 feet(Case International 2013). A 6.5-foot long cylinder and 7 foot long header leaves 5 feet of length to add feeder housings and straw processing.

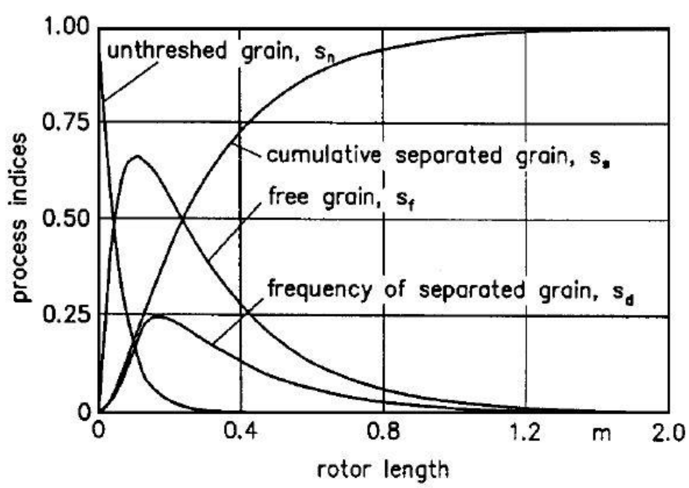


Figure 22: Threshed and separated grain versus rotor length(Stout et al. 1999)

Chapter 6. Functional Comparisons

The proposed autonomous harvesting system offers an opportunity to examine operational differences that a smaller, automated can provide. Smaller equipment, using differential steering and path planning, can provide a distinct advantage over conventional systems. This section will examine the differences between the two systems in several areas: field layouts, efficiencies, speed, and resources.

6.1 Field Scenarios

Field sizes and shapes vary wildly. They can range in size from an acre or less to several square miles. In order to evaluate the effectiveness of the proposed system in two different scenarios will be discussed: a quarter section and an irregularly shaped field. Much of the Midwest is divided into quarter sections because the land was divided up at a time when the land was uninhabited, and the land is flat and without obstructions. In other parts of the country, such as farms on the east coast, the land is frequently divided into much smaller fields, oftentimes irregularly shaped due to land features like mountains and rivers. While a great deal of the land used for crop production exists in the section-layouts, it is important to examine what, if any, effect field size and shape have on the proposed autonomous system.

Without exact field dimensions, it is impossible to calculate the time savings that can be gained through automation and path planning. However, research has been performed on the ability of path planning algorithms to minimize travel distances compared to human path planning. Using a Ford 6440 tractor and a disk harrow, Bochtis and Vougioukas demonstrated that optimal sequence generation using automation provided a distance savings of 13.6%, 27.1%, and 54.27% over a human operator(D. D. Bochtis and Vougioukas 2008). In tests of an algorithm in Finnish fields, Okasanen and Visala were able to reduce the overhead time by an average of 29%, and had a decrease of more than 50% in 15% of cases(Oksanen and Visala 2009). This case is particularly insightful because of the ability to handle complex fields, as seen in Figure 23, which shows typical fields from this experiment.

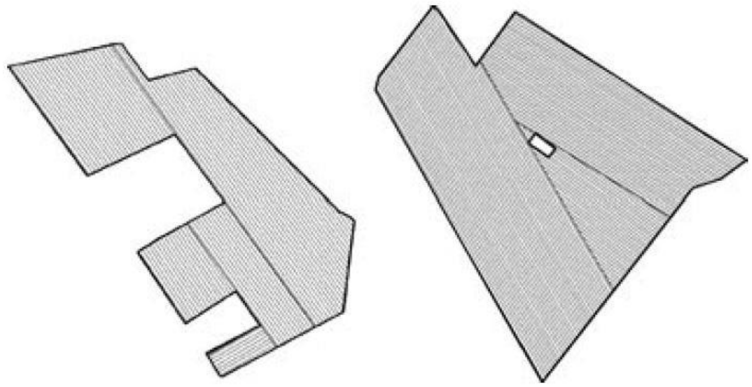


Figure 23: Typical fields in Okasanen and Visala study(Oksanen and Visala 2009)

Harvesting automation productivity gains over human operators will be lower than the studies shown above because harvesting must follow the rows of the crop. However, a differentially driven robot provides a distinct advantage over other harvest methods. The ability to move with arbitrarily small turning radii allows the harvester to minimize the distance and time travelled outside the row. Applying this trait to the differences between a quarter section and an irregularly shaped field gives some insight into the proposed harvester's performance. An irregular field may have more turns, depending on size and layout, than a quarter section. In that situation, as well as any turns that require a small turning radius, the proposed system would provide distinct advantages over a conventional system. However, in a long, narrow field that has fewer turns, there would be less of an advantage.

6.2 Custom Operators

Custom operators provide harvest services to farmers who cannot justify owning combines. Using the same combine model developed in Chapter 5, a comparison of the available technologies is performed. Data for custom harvester usage is taken from the 2011 Harvest Year Report for USCHI's Custom Harvester Analysis and Management Program(USCHI's Custom Harvester Analysis and Managment Program 2011).

As a way of validating the model for both the proposed and conventional harvesters, a comparison between the model and the survey data was performed. The average harvest acreage of 6639 acres was used as the main input for the model, and parameters such as loan repayment periods were adjusted to reflect the shorter ownership period of custom equipment. The ownership period used in this calculation was 2.4 years, the average length of ownership from the survey data. The results of this comparison are shown below in Table 6.

Table 6: Model vs USCHI survey comparison

	Model	Survey	Difference
Seperator Hours	521.6	454	15%
Engine Hours	745.2	628	19%
Fuel and Lubrication	$51,247.62	$45,797.00	12%
Repair and Maintenance	$17,719.95	$19,779.00	-10%

The results show some difference between the model and survey data, particularly with respect to the separator and engine hours. The assumptions built into the model, such as field efficiency, are discussed in Chapter 5 and provide insight into the source of some of the differences. The 70% field efficiency used in the model may vary from the efficiency of a professional harvesting crew, who have more experience and more incentive to finish in the shortest time possible. Custom operators also likely operate their machines faster than the 5 mph assumed in the model. It is also important to note that the survey data includes harvest of a wide range of crops, including wheat, corn, soybeans, barley, and others which change the operating characteristics of the combine.

The results of analysis for custom harvesters are shown in Table 7. The shorter ownership lifespan of a custom combine creates several differences between this analysis and the analysis presented in Chapter 4. For each system, the much shorter ownership period leads to lower finance costs, lower depreciation, and lower maintenance costs, but the higher usage gives higher fuel and labor costs. When comparing numbers between analyses it's important to remember that the different timescales have significant effect on the costs. For example, for a conventional harvester in the 640-acre farm scenario, fuel costs are $74,173 and for the custom harvest scenario fuel costs are $126,048. While this appears to be a moderate increase, the custom harvest scenario takes place in roughly one quarter of the time.

As seen in Table 7, the proposed system has less total cost than a conventional system, but greater costs than the autonomous system of conventional size. This matches expectations for this analysis, as the larger equipment will be able to harvest crops at a higher rate than smaller equipment. The efficiency advantage of the large autonomous system allows outweighs the higher cost. Additionally, the ability to harvest more acres in a shorter amount of time means that a custom operator can harvest for more people, increasing income.

Table 7: Custom harvesting total cost of ownership comparison

Total Costs												
Fixed Costs												
	Proposed				Conventional				Autonomous Conventional			
	Per acre	Per hour	Annual	Lifetime Total	Per acre	Per hour	Annual	Lifetime Total	Per acre	Per hour	Annual	Lifetime Total
Interest	$ 1.52	$ 12.41	$ 10,072.76	$ 24,174.62	$ 1.56	$ 13.88	$ 10,341.36	$ 24,819.27	$ 1.76	$ 15.68	$ 11,684.40	$ 28,042.56
Depreciation	$ 16.98	$ 138.93	$ 112,729.98	$ 270,551.96	$ 17.06	$ 151.96	$ 113,241.56	$ 271,779.75	$ 17.18	$ 153.02	$ 114,027.92	$ 273,667.00
Insurance	$ 0.28	$ 2.31	$ 1,875.00	$ 4,500.00	$ 0.29	$ 2.58	$ 1,925.00	$ 4,620.00	$ 0.33	$ 2.92	$ 2,175.00	$ 5,220.00
Housing	$ 0.08	$ 0.64	$ 520.31	$ 1,248.75	$ 0.09	$ 0.81	$ 601.25	$ 6,012.50	$ 0.09	$ 0.81	$ 601.25	$ 1,443.00
Subtotal	**$ 18.86**	**$ 154.29**	**$ 125,198.05**	**$ 300,475.33**	**$ 19.00**	**$ 169.23**	**$ 126,109.18**	**$ 307,231.52**	**$ 19.35**	**$ 172.42**	**$ 128,488.57**	**$ 308,372.56**
Varible Costs												
	Proposed				Conventional				Autonomous Conventional			
	Per acre	Per hour	Annual	Lifetime Total	Per acre	Per hour	Annual	Lifetime Total	Per acre	Per hour	Annual	Lifetime Total
Maintenance	$ 3.87	$ 31.69	$ 25,714.58	$ 61,715.00	$ 3.34	$ 29.72	$ 22,149.94	$ 53,159.86	$ 1.49	$ 20.72	$ 9,888.15	$ 23,731.55
Fuel	$ 5.10	$ 41.73	$ 33,864.35	$ 83,813.46	$ 7.67	$ 68.34	$ 50,929.32	$ 126,048.85	$ 5.97	$ 82.99	$ 40,849.16	$ 98,037.99
Lubrication	$ 0.77	$ 6.26	$ 5,079.65	$ 12,572.02	$ 1.15	$ 10.25	$ 7,639.40	$ 18,907.33	$ 0.89	$ 12.45	$ 5,941.75	$ 14,705.70
Labor	$ 2.11	$ 15.00	$ 13,997.23	$ 33,593.34	$ 1.59	$ 12.35	$ 10,583.62	$ 25,400.68	$ 1.24	$ 15.00	$ 8,233.66	$ 19,760.79
Subtotal	**$ 11.85**	**$ 94.68**	**$ 78,655.81**	**$ 191,693.81**	**$ 13.75**	**$ 120.67**	**$ 91,302.27**	**$ 223,516.71**	**$ 9.59**	**$ 131.15**	**$ 64,912.73**	**$ 156,236.04**
Total	**$ 30.71**	**$ 248.98**	**$ 203,853.86**	**$ 492,169.15**	**$ 32.75**	**$ 289.90**	**$ 217,411.45**	**$ 530,748.24**	**$ 28.94**	**$ 303.58**	**$ 193,401.29**	**$ 464,608.59**

6.3 Efficiency

There are several ways to evaluate the efficiency of a harvester. For the proposed system, field efficiency has been discussed extensively, but fuel efficiency and man-power efficiency are both metrics that can be used to evaluate the effectiveness of the harvest.

Fuel efficiency is one measure of harvest efficiency. Fuel consumption for equipment is usually measured in gallons per hour, but the calculations performed for the analysis presented in this thesis provide an estimated gallons per acre, as well. The proposed system uses 1.33 gallons per acre, while the conventional system uses 1.51 gallons per acre and the autonomous conventional system uses 1.41 gallons per acre. The proposed system's fuel efficiency advantage is largely a result of the smaller engine. The conventional systems' larger engines are the main cause of higher fuel usage, and while the autonomous system uses more fuel per hour, it also covers more acres per hour, giving it a slight advantage over the conventional system.

Labor efficiency is difficult to measure with the autonomous systems, as one person can operate/supervise several different harvesters. In a conventional harvester, an operator can cover 9.4 acres per hour using a 12 row head(Iowa State University Extension Service 2009). One of the proposed autonomous harvesters can cover 3.03 acres per hour, but one operator can supervise more than one of the proposed harvester. If the farm can justify owning 3 or more autonomous harvesters, the manpower needed per acre is lower than a conventional system. The proposed system has the ability to use less labor than a conventional system, but that is contingent on the size of the farm and the amount of harvesters used.

The proposed system has several efficiency advantages over conventional technology. The higher field efficiency leads to higher fuel efficiency, and the ability for one person to control multiple harvesters allows the system to be a more efficient use of labor, if enough machines are used.

6.4 Safety

The safety of the proposed system is an important consideration in the sensing design, software design, and overall function of the harvester. Farming is a dangerous occupation, and harvesters were the cause of death for 253 people between 1992 and 2001(Center for Disease Control Workplace Safety and Health 2004). One goal of the proposed system is to increase safety, which will be accomplished by reducing the size of the equipment and removing the operator from vehicle. Research in the area of machine learning has developed techniques that combine color images and depth information to identify humans in unstructured environments(Stentz et al.)(Berggren and Orklund 2012). Being able to identify a human partially obscured by corn plants or as they approach the harvester will give the ability to shut down the system to prevent injury to a human. Safety of the operators and bystanders is incredibly important to both the function of the harvester and the future of agricultural robotics. If an autonomous system developed a reputation of being unsafe, it would have a negative effect on the viability of autonomous systems in the future.

6.5 Liability

The legal implications of increasing autonomy are an ongoing area of discussion and research in the field of robotics. Much of the discussion focuses on who is at fault when events such as the death of a bystander occur. Several steps could be taken to minimize the liability faced by the equipment manufacturer. Designing, building, testing, and proving the reliability of the safety system that identifies humans and does not allow operation with them nearby is critical to the success of the robot. Requiring direct control from an operator when someone is inside the safety envelope would allow an operator to take control and responsibility for the safe operation of the harvester. Other actions to limit the liability faced by the equipment manufacture include establishing operation guidelines that ensure safety of the bystanders, such as posting signage and restricting access to a field when autonomous harvesters are operating.

Guidelines for safe system operation should be developed to ensure the safety of people near the harvester, not just to limit the liability faced by the equipment manufacturer. With appropriate guidelines, the safety of the system can be increased and liability for accidents can be clearly determined.

Chapter 7. Conclusion

In the final chapter of this thesis, the major advantages and disadvantages of the proposed system that were discussed previously will be presented, and areas of future work will be discussed.

7.1 Conclusions

This thesis has shown that it is possible to build a small autonomous system that is economically advantageous as compared to conventional systems. For an average sized farm, if an individual harvester costs less than $141,000 it will be cheaper to own and operate an autonomous 3-harvester system for 10 years than a conventional system. The proposed system also reduces the size of the smallest economically viable farm, from 2000 acres for a conventional harvester to 461 acres for the proposed harvester. This meets the initial goals of increasing farming profitability and reducing some of the risk absorbed by the farmer.

A design for an autonomous system was proposed. This system is smaller, more maneuverable, and more fuel-efficient that a conventional system. Utilizing hydrostatic drive and a differential drive platform, the powertrain provides power, variable speed, and the ability to perform zero-radius turns, simplifying the control and path planning algorithms. The field efficiency advantage conferred by intelligent path planning and harvester agility provides significant benefits in the harvest economics.

Functionally, the smaller proposed system has several advantages. Path planning software performs better than humans in choosing a route through the field, and has significant advantages in smaller, irregularly shaped fields. The proposed system cannot outperform a conventional system in custom harvesting applications, but is more fuel-efficient and has the potential to use less manpower.

Most importantly, this thesis poses a question of feasibility and outlines a method for answering which compares proposed and conventional equipment. Similar calculations can be performed for more refined harvester models, tractors and other implements, as well as a host of other processes where maximizing operator output is now meeting increasing automation, such as mining equipment.

7.2 Future Work

A conceptual design is the very beginning steps of designing and building a successful system. In order for this design to proceed many future steps need to take place, both in the design of the harvester itself and in the state of the art of autonomy.

7.2.1. Harvester Design

The harvester itself needs a detailed design. Design specifics such as cylinder diameter, feederhouse and grain elevator design, component layout, motors and actuators, and other parts of the harvester must be developed in detail. Some specifics such as the design of threshing system, must be designed, prototyped, tested, and iterated to have a successful product. After the larger details are designed, a detailed design of the whole harvester and reliability testing must be performed. Another important area of research and future development is the modularity of autonomy systems. If the sensors and actuators required for autonomy could be transferred across equipment, the cost of ownership could be spread across several pieces of equipment.

7.2.2. Software Design

The software necessary for a successful harvester must be developed before a product can be released. A method for determining field boundary, row direction, and the optimal path for harvest must be developed as well as an interface for the farmer. A method for querying human operators when the harvester encounters a situation that it can’t handle must be created, as well as way to prioritize those requests and have a human take over control of the harvester. Some of these challenges may be eased by using information from planting, especially determining field layout and row directions. However, using this information would require a means of recording the information from the tractor, saving it for the season, and using it during the harvest.

7.2.3. Safety

The safety of the system is critically important to the viability of the harvester and the overall fortunes of autonomous agriculture. Applied autonomy is a relatively young field, and if it developed a reputation of being unsafe it would sour public opinion and damage the future of autonomy. There is a great deal of work being done in the area of safety involving autonomy, both in identifying and in protecting humans. Machine learning algorithms that identify humans in obscured and otherwise unfavorable conditions are being researched, and these technologies need to be optimized and applied to autonomous systems to maintain an excellent safety record and reputation.

7.2.4. Autonomous Systems Management Research

There is practically zero data concerning the management of autonomous systems. No published data exists for the differences between the maintenance and ownership costs of autonomous and conventional systems. No published data exists on the economic effects of the increased depreciation experienced by electronics on the overall salvage value of equipment. More research in these and other areas specific to owning and operating autonomous equipment will help enterprise owners make more informed purchasing and operating decisions.

Autonomy is a young field that is constantly expanding. Continuing work and research will help advance the field of autonomous agriculture and autonomy as a whole. With significant research and development, it is possible to build a small autonomous harvester that can compete with larger systems.

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