INITIAL POSSIBILITIES FOR ROBOTIC COTTON HARVEST

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Abstract

Stationary robots are already accomplishing many critical industrial manufacturing steps. As these robots are combined with other technologies (e.g., self-driving cars, and high-throughput phenotyping) agricultural efficiency could continue to increase. Commercial autonomous robots currently provide in-row weeding and both ground and aerial spraying. There will be substantial investment in agricultural robots for weed control tasks since herbicide resistant weeds are a threat to multiple crops on a billion plus acres. However, investment will likely lag for small-acreage, unique-applications such as cotton harvesting. This paper reviews the early stage design of cotton harvest systems that could be developed as attachments for commercial multiple task Ag Robots, including a plan for the economic analysis of these systems and a review of studies to access the potential fiber quality benefits from frequent harvest. Frequent harvest of cotton (~25 times per season) should provide: reduce risk from complete crop loss due to major weather events like hurricanes; less aphid and whitefly damage; better fiber quality by minimizing weathering and reduce cleaning needed at gin; increased uniformity of all fiber properties by harvesting bolls subject to the same environmental conditions during fiber formation; ability to adjust the number of robots to match cotton acres; the potential to be solar powered, reducing fuel costs and lowering GHG emissions; a multifunctional tool capable tasks such as weed control, pest scouting, and spraying. This project is a feasibility study to see if small autonomous robots will have an economic advantage over large machines and that question remains unanswered at this time. However, short-term results have immediate application such as machine vision for contamination detection at the gin and improving our ability to do high throughput phenotyping for cotton breeders.

Introduction

Robotics are already a key component of assembly line processes for many industries such as automotive manufacturing. As these robots are combined with other technologies (self-driving cars, high-throughput phenotyping, remote sensing and data analytics) agricultural efficiency will be a major beneficiary. Already commercial Ag robots provide in-row weeding and both ground and aerial spraying. There will be substantial investment in Ag robots to accomplish these tasks since they are applicable to multiple crops on a billion plus acres. However, investment will likely lag for small-acreage, unique-applications such as cotton harvesting. For this reason, and the benefits discussed below, Cotton Incorporated is investing in two unique cotton components of Ag Robots: (1) early stage design of diverse cotton harvest systems that hopefully can be developed as attachments for commercial multiple task Ag Robots, especially weed control and (2) cotton varieties optimized for harvest by these systems. Based on results of these first two components, future investment could include evaluation of agronomic adjustments to the current field pattern including: plant spacing (in-row and between-row), ground configuration (flat, bedded, wide-bed, etc.), and row configuration (row length, slope, etc.) to facilitate the new Ag Robot season-long system. Harvest is set as the highest priority as the current mechanical harvest system for cotton: is expensive; has plastic contamination risk; requires a large area per machine (~2000 acres); could lead to soil compaction under wet harvest conditions; and the machine is sole dedicated to cotton, often sitting idle for 10 months of the year.

Benefits of Harvest with Small Robots

Freed of the need for a human driver, the size of future farm equipment (Ag robots) can be adjusted to the task. Small in-row cotton pickers that function like hand picking could provide many benefits as listed below.

- Fiber quality would improve dramatically (see section on Fiber Quality Implications later in this paper):
    - Bolls are picked as soon as they open to avoid yield and quality loss from rain, wind, disease (hardlock/boll rots) and insect residues.
    - Bolls would have less potential to be impacted by sand storms, reducing needle abrasion in woven textiles.
    - Top bolls could reach maximum maturity that the seasonal heat units allow.
    - Immature bolls at the top could be harvested and marketed separately to capture a premium for uniform low mic cotton in industrial applications.
    - High mic bolls would also be harvested and could be marketed separately for specialty uses such as premium towels.
    - Bolls harvested on any one date would achieve an unprecedented level of fiber uniformity since they would all have experienced similar weather and plant conditions (some control based on within variability will be needed to maximize the uniformity). Theoretically, bolls could further be sorted by fruiting position if determined economically worthy, leading to even greater uniformity and marketability.
    - Leaf and bract trash in the seed cotton would be significantly reduced allowing faster ginning with less cleaning.
    - Zero contamination (plastic bags, mulches, sticky cotton) is easier to achieve since the robot would recognize and grab only cotton fiber.
- Harvest aids could be eliminated (or reduced) saving costs, allowing leaves to stay on the plants and protect developing and newly opened bolls from wind damage.
- In-row robot pickers would be viable for both large and small producers as Ag robots will likely follow Ag drone costs downward and suppliers upward.
- Increased soil compaction could be eliminated at harvest.
- The yield versus quality tradeoff would be eliminated between picking and stripping in TX and OK, since a robot would harvest a high percentage of the crop (even immature bolls if so desired) but these would not be comingled with the mature bolls.
- Harvest robots would allow for quicker return to the field after a rain event due to less weight reducing field disturbance compared to a traditional machine harvester.
- In the future, a harvest robot could be paired with ginning either on the harvester or on an edge of field robot.
- Assuming several small robots, failure of one robot would have a more limited impact on harvest progress compared to a single machine covering 80 acres per day.
- Large, expensive harvest machines would not be sitting idle for up to 11 months. Robotic platform could multi-task other operations such as scouting, weeding, pest control and be crop agnostic.

As companies race to develop artificial intelligence (A.I.) capabilities, applications in agriculture will become even more apparent. The development of autonomous Ag robots will expedite the application of A.I. in agriculture by providing platforms that can gather site specific data and work with minimal human labor and time inputs.

Current Applications of Robotics to Agricultural Field Operations

Several examples are emerging of robotic applications in agriculture and a recent review of robotic applications for weed management, scouting and harvest are given by Shamshiri et al. (2018). These include commercial or near commercial systems:

- Robots design for agricultural applications have developed by Dorhout R&D LLC in Iowa: http://dorhoutrd.com/robotics.
- A robotic cultivator for greenhouse use is available from the French company Naio (google chrome does a pretty good job of translating from French to English): http://www.naio-technologies.com/machines-agricoles/robot-de-desherbage-oz/.
- Autonomous sprayers are commercially available in Australia from Swarm Farm: http://www.swarmfarm.com/.
- Under canopy phenotyping robots are commercially available for as little as $5000 per unit: https://www.earthsense.co/home/.
- A prototype robotic harvester is in development in India by GRoboMac: http://www.grobomac.com/.
- ecoRobotix www.ecorobotix.com/en, developer of the Swiss weeder, believes its design could reduce the amount of herbicide farmers use by 20 times.
- Fendt, a division of AGCO, has a prototype set of swarm bots for planting operations: https://www.fendt.com/uk/xaver.html.

And prototype systems that have been built by researchers at public institutions:

- Low profile autonomous soil and foliage scouts are available in New Zealand that pass underneath a two-wire sheep fence. http://www.agresearch.co.nz/news/mars-to-manawatu-for-robotic-rover-project/.
- Considerations of solar power for ag robots is discussed in the thesis at: http://www.doria.fi/bitstream/handle/10024/98944/Yury%20Kuritsyn.%20Master%20thesis.%20Energy%20and%20Dynamics%20of%20the%20solar%20agricultural%20robot%20SolarSprayer.pdf?sequence=2.
- An overview of several agricultural robots, including strawberry and apple harvest systems are presented at: https://www.techemergence.com/agricultural-robots-present-future-applications/.
- The University of Sydney has developed several robots to support agricultural applications, particularly for vegetables: https://mashable.com/2017/10/17/robotic-farming-innovations-automate-farming.

Considering the uniqueness of cotton harvest and the economic desire to utilize a robot platform year round for multiple tasks, it is imperative that Cotton Incorporated aggressively develop working harvester attachment prototypes that can be used by commercial robot providers to design their multifunctional equipment. Part of the high cost of cotton harvesting is its single use (unlike a combine harvester), the robot harvester initiative provides the cotton industry the opportunity to break the capital cost of leaving harvesters in the shed for 10 to 11 months out of the year. Work in this area is already in process in India and China where they have also made progress to use machine vision to identify cotton bolls and have proposed a vacuum system for boll removal using a robotic arm (Rao, 2013; Wang et al., 2008; Bhattacharya et al., 2013). Additional work has also been done in Australia to use machine vision on a robotic platform to measure internodal distances in actively growing cotton fields (McCarthy et al., 2009; 2010).

Overview of Cotton Incorporated Funded Robotic Research

Current Cotton Incorporated research projects are designed to accelerate progress towards robotic applications in cotton including the work to use sensors to measure various plant parameters in high throughput phenotyping (HTP) for cotton breeders, and progress in unmanned aerial systems (UAV, i.e., drones). For example, Figure 1 is a three-dimensional representation of a cotton plant derived from a sensor that uses lasers to determine how far away an object is from the unit (LIDAR, Light Detection and Ranging). The ability to automatically find cotton bolls in three-dimensions is an important step for robotic cotton harvest. The work has been conducted at the USDA, Agricultural Research Service in Maricopa, AZ. Progress on machine vision to classify cotton bolls using UAV images has also been made by researchers at Texas A&M and at the University of Georgia using a stereoscopic vision system.

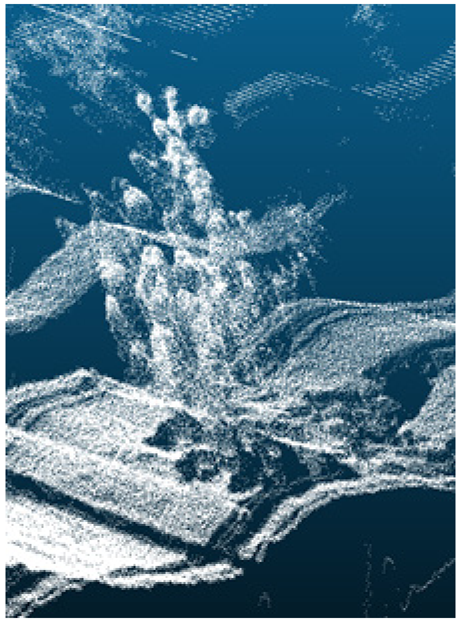

Figure 1. Three-dimensional point cloud of a cotton plant derived from a LIDAR sensor (image complements of USDA-ARS, Maricopa, AZ).

In 2018, there are six Cotton Incorporated projects devoted to further exploring robotic harvest. A majority of these projects have more detailed papers in these proceedings. Dr. Joe Mari Maja at Clemson University (Edisto Research & Education Center) has purchased a robotic platform from Clearpath Robotics (https://www.clearpathrobotics.com/robots/). The specific model ordered is the Husky (https://www.clearpathrobotics.com/husky-unmanned-ground-vehicle-robot/) and it will fit between cotton rows with a tire to tire width of 26 inches. The system comes with pre-built accessories to make customization fairly simple. Dr. Maja is evaluating different approaches to adapt this platform for cotton harvest. A photograph of the Clemson platform in skip row cotton (38-inch row – so planted row every 76-inches) is provided in Figure 2.

Figure 2. Clemson robot with harvest platform in skip row cotton field (76-inches between planted rows).

Dr. Glen Rains at the University of Georgia in Tifton has developed a stereoscopic imaging system that can classify defoliated cotton plants from a moving platform at 1.5 mph. He is also experimenting with ways to harvest the bolls using a vacuum system. The feasibility of ginning the cotton during the robotic harvest process is being evaluated by Dr. Alex Thomason at Texas A&M. The economic design parameters for cost efficient robot harvesting is investigated by Agricultural Economists Terry Griffin and Gregg Ibendahl at Kansas State University under the supervision of Jon Devine, Senior Economist at Cotton Incorporated (Cullop et al., 2018). Plant and boll conformation is under investigation by Dr. Brian Ayre at the University of North Texas in collaboration with USDA-ARS and Texas A&M cotton breeders.

Drs. Gaylon Morgan and Emi Kimura at Texas A&M, along with Dr. John Snider at University of Georgia conducted a frequent hand harvest study in 2018 to better understand the fiber quality implications of multiple harvest compared to a single one-pass methods. The Texas A&M study also includes a fruiting position by node component to better understand fiber quality characteristics on cotton plants. In 2019 an addition study site will be added in west Tennessee under the direction of Dr. Tyson Raper at the University of Tennessee.

Design Considerations for Robotic Cotton Harvest

A review of days suitable for field work has shown that on average, the most efficient cotton harvester can cover approximately 2000 acres per season (Griffin, et al. 2015; Griffin and Barnes, 2017). Assuming a discounted purchase price for a new CP690 cotton picker from John Deere of $700,000, this corresponds to $350 per acre in hardware costs for harvest. This scenario is what is used for comparison with a robotic system.

Work is in process for a more comprehensive costs comparison in terms of costs per acre (Cullop et al., 2018), and recent studies suggest current harvest costs of $60/acre, excluding the cost of defoliation that is approximately an additional $10 to $15 per acre (Martin and Valco, 2008). Another potential shift lies in taking advantage of the longer harvest window by switching from fuel to solar, which again results in a significant transformation in the underlying economics as significant fuel costs are alleviated. Other aspects that favorably alter economics is when robots become multi-purpose; for example, a weed and pest scouting robot that adapts to harvesting is able to spread fixed costs from harvest-only to other tasks such as agronomic scouting and pest control. Essentially, performing additional tasks reduces machinery per acre costs for every trip across the field. Further economic advantages become available when one adds the ability to perform continuous weeding and spot pesticide spraying. If the system included a tool-barn where the robot could go and swap out tooling, recharge, re-fill; the potential for a one-platform multi-use system becomes very interesting and ideally the economic analysis could help highlight key aspects to help direct the development efforts.

Time-In-Motion Data

For preliminary analysis, the following assumptions were made:

- Single row robotic harvester (harvest one side of each row {2 half rows} it is passing between)
- 40-inch row spacing
- 3 mph travel speed down the rows with an average length of 0.3 miles
- 25 passes through the field yielding an average of 1500 pounds of fiber per acre
- Robot able to store 3 lbs of fiber (~8 lbs of seed cotton) and unload in 12 seconds
- Each robot covers 11 acres ($4000 robot would equal hardware costs of current picker)
- ’ 10 hours to harvest 11 acres per harvest cycle (250 hours total operation time)

Completion of harvest in a 10 hour day is important as it is assumed that even with robotic harvest, there will be times cotton is too wet for storage (must stay below 12% w.b. moisture content). Important design variables from a time-in-motion perspective are the number of passes during the season and the cotton storage capacity on the robot. For example, assuming 25 passes during the season in a 1500 lb per acre field, Figure 3 shows the impact of changing storage capacity. From the figure it is clear in this scenario, 3 pounds of fiber storage (~8 lb seed cotton) is adequate when considering the time needed to unload the robot. If the number of harvest cycles are decreased, the optimal storage capacity will increase. Furthermore, if desirable to have the harvesting robot carry the material to the end of the row, capacity would likely need to be increased. Using the 25 harvest cycles with a 1500 pound per acre yield scenario (40 inch row spacing), one pound of cotton would be harvested every 218 feet of row length traveled. Therefore, to reach the end of a 0.3 mile long row, 7.3 pounds of fiber capacity (18 pound seed cotton) would be needed. A row length of 0.3 miles is used as Yan and Roy (2016) determined 50% of U.S. cotton fields are less than 100 acres with the highest frequency of fields with dimensions of 0.25 x 0.25 miles (40 acres). Hardin and Searcy (2008) reported literature values of 6 pound of seed cotton per cubic foot for cotton loaded in to trailers. Using this density would require a minimal storage volume of 3 cubic feet.

For the scenario of 25 harvest passes and a 1500 pound per acre yield, assuming the yield is equally distributed during the season, the effective yield per pass is 60 pounds per acre. Data from the Regional Breeders Testing Network (RBTN, 2017) shows that an average cotton boll contains 2.2 grams of fiber (0.0049 lb), so there are 12,382 bolls per acre per harvest cycle. For the 3 mph scenario previously considered, this corresponds to 1.1 acres per hour, so this would correspond to the need to harvest approximately 4 bolls per second. It is envisioned the robot could contain multiple “arms” or “spears” on each side to enable boll removal at this rate.

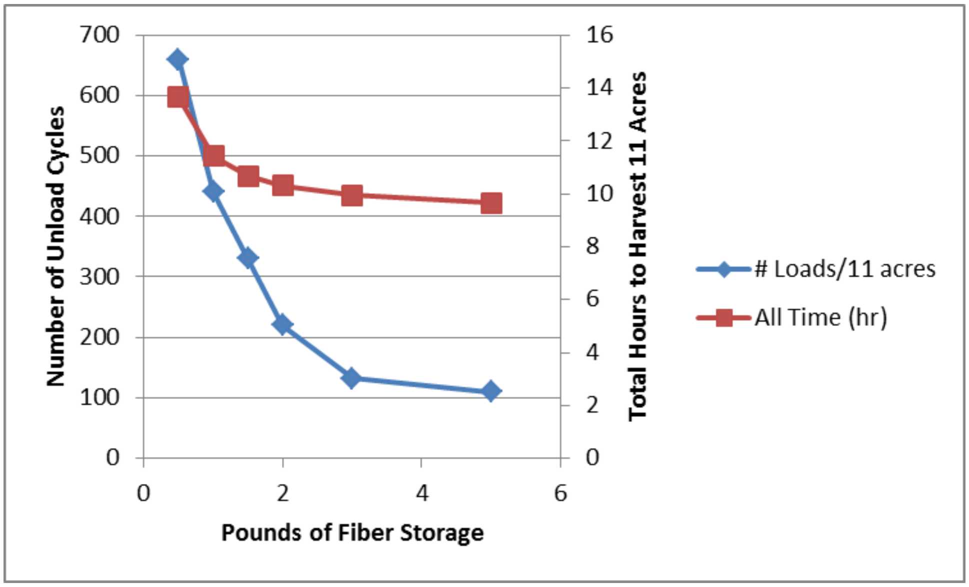

Figure 3. Impact of storage capacity on the number of unload cycles and total time to harvest 11 acres of 1500 lb per acre yielding cotton with 25 harvest cycles. Blue line (left axis) is the number of times the robot would have to unload for a given amount of storage capacity (x-axis). The red line (right axis) represents the total hours to harvest 11 acres.

Once a system is developed to remove the seed cotton from the plant, the next challenge is to find the most optimal method to compact the material and remove it from the field. One possible solution would be to mimic the traditional module building system: a harvest robot has limited storage capacity that contacts a transportation robot to collect material when full. That robot then transports to an edge of field compaction unit (module builder). Initial reaction to this approach from a group of cotton producers was not positive - they appreciate the easy of handling and improved production afforded by the round modules produced by the current John Deere module building harvesters (MBH). An alternative would be to have the harvesting robot compact the harvested cotton and then “package” it and leave in the row for later retrieval. The challenge becomes finding a package / covering that has low potential to later contaminate the cotton and is affordable. Also, finding the optimal surface area to volume ratio needs to be considered.

Implications for Cotton Ginning

Even if on-board ginning is not feasible, precise harvest of only the fiber and seed would greatly decrease the amount of processing at the cotton gin. The process would go from something like a minimal process for picker cotton of:

1. Module feeder
2. Plastic removal machine [Future]
3. Dryer
4. Stick machine
5. Burr machine
6. Extractor / feeder above gin stand\
7. Gin stand
8. Lint cleaner 1
9. Lint cleaner 2
10. Bale press

With robotically harvested cotton, it would be reduced to:

1. Module feeder
2. Dryer [may need to harvest cotton when wetter than optimal]
3. Extractor / feeder [catch anything that may have slipped in]
4. Gin Stand
5. Bale press

Not only would this reduce ginning costs, it should also better preserve fiber quality relative to the current harvest system.

Fiber Quality Implications of Robotic Harvest

Other potential economic advantages could come from the increase in fiber quality by reducing the exposure time of bolls as well as increase the uniformity of fiber quality. Past studies have shown that fiber quality measures generally decrease in desirability from a woven textile perspective from the top to the bottom of the plant (Kothari et al., 2015). Therefore, the ability to segregate bolls from the same portions of the plant will greatly increase the uniformity of the fiber's properties. Variation in crop development due to within field variables such as soil type would also need to addressed as abiotic stress can induce variation in fiber properties, especially micronaire and fiber length (Ge et al., 2008).

Additional fiber quality benefits include the limited amount of early maturing bolls would be exposed to the elements, as well as risk from insect droppings and sand entrapment. Using data from USDA (2018), the date when 50% of acres in state were planted, had open bolls and were harvest was determined based on 5 year average conditions ending with the 2017 crop season. From that data, the average time between open boll and harvest is 47 days. Not only can fiber quality be compromised during that time period, but there are also risk that bolls could be lost due to extreme rain or wind events during this time. All this translates into a cost to delayed harvest that can occur when weather conditions are not ideal for defoliation – for example, estimates of $13 per acre per week of delayed harvest was estimated in Georgia (Shurley and Bednarz, 2001).

Other Issues Associated with Robotic Cotton Farming

If the analysis from early data collection in this initiative is promising, several additional challenges and opportunities will need to be addressed in the future as discussed in the following sections.

Cotton Plant Manipulation for Robotic Harvesters

The timelines for development of a commercial robotic cotton harvester allow the co-development of commercial varieties and agronomic systems better suited for multiple-pass, non-defoliated harvesting in cotton and application of robots in rotational crops. Plant architecture genes that control cotton fruiting and branching have been identified and shown amenable to genetic manipulation for specific plant outcomes (McGarry et al., 2016). Cotton leaf shape genes can also be manipulated to achieve diverse leaf outcomes (Andres et al., 2016). Boll type resources are also available in open (non-protected) germplasm: stringy bolls in SG501, pendant bolls in HS26, big and non-stormproof bolls in DP50, loose fiber to seed attachment in DP5690, and cluster bolls in DP90. Agronomic adjustments can also shift plant architecture. For example, high density planting shifts >80% of the bolls to 1st position fruiting sites. In the short-term, manipulation of plant growth with plant growth regulators will be paramount to ensure correct plant architecture and feasible robotic harvesting. Shorter statured and upright plants should allow for more efficient robotic harvesting.

Pest Challenges

Two other challenges now facing cotton producers are increased pest resistance, particularly glyphosate resistance weeds (Norsworthy et al., 2014, 2016), and early indications of bollworm resistance to Bt cotton (genetically modified cotton that contains genes for an insecticide). The challenge of herbicide resistant weeds is exacerbated by the lack of new herbicide mode of actions and there are many anecdotal reports of farmers forced to utilize hoe crews to achieve the needed weed control. Increased bollworm pressure would also require cotton farmers to increase the amount of scouting conducted in their fields to determine if the insect numbers have exceeded an economic threshold. UAV data over research plots have been successfully used to estimate crop height. The measures of crop height taken multiple times during the year gives an estimate of growth rates that can be further interpreted to overall plant health and development stage. Ultimately these UAV images could automatically guide the ground-based robots to areas of the field where there are problems to either take action such as removing weeds or collect more detailed images for review by the farm's consultant. Further discussion of the opportunities for robotic weed control is provided by Westwood et al. (2018) as part of a paper examining the future of weed science.

Social Implications of Robotic Cotton Harvest

There is a great deal of societal concern about the use of robots in replacing human labor and creating employment crisis across many disciplines, not just agriculture. In the case of labor for cotton harvest where mechanization is already prevalent, the impact on labor requirements will not be significant, as one to two employees are currently all that are needed to harvest approximately 2000 acres per year. However, in parts of the world such as eastern China and much of India where cotton is still hand harvested, the impacts on farm labor are of more concern. Some lessons learned from the first wave of cotton harvest mechanization could help inform how robotic harvest may impact hand-harvested areas of the world.

Figure 4 shows the adoption rate of machine harvested cotton in the U.S. The first commercial cotton picker was available in 1943 and from the figure it is clear that it took 10 years before more than 20% of the crop was machine harvested. Several have speculated about the forces that drove the ultimate adoption of machine harvest in the U.S., with labor shortages being a significant, but only partial explanation for the early adoption in some regions (Waggoner, 2004). Ultimately there is evidence that when yields became high and the per acre costs of the technology was lowered, workers were likely displaced by mechanization (Grove and Heinicke, 2003).

The World Bank recently completed a study on the potential societal impacts of cotton harvest mechanization in Uzbekistan (Swinkels et al., 2016). From that study they concluded there would be situations where alternative incoming-earning opportunities would need to be created in the short-term, particularly to support women in rural communities if mechanical cotton harvest is widely adopted. The report offers several measures that could be taken to minimize the negative impacts of mechanization, and the overall report does suggest the societal impact of robotic harvest on non-mechanized rural communities will have to be considered.

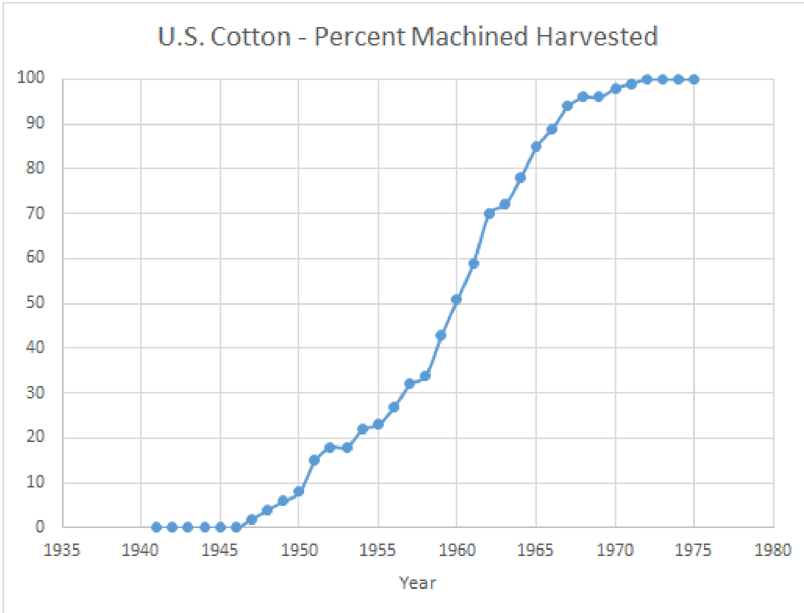

Figure 4. Percent of U.S. cotton machine harvested from 1941 to 1975 (compiled from USDA, Economic Research "Cotton Ginning Charges, Harvesting Practices, and Selected Marketing Costs" reports).

Summary

There are clear benefits from the ability to frequently harvest cotton with a robotic system including fiber quality improvements and reduced risk of yield loss due to weather events. Robotic technologies are evolving quickly and there are already examples of commercially available systems for robotic weed control. Based on the first year of testing at Clemson University and the University of Georgia, it is clear the technology exist to use a robot to autonomously harvest cotton at this time and the question still to be answered is can it be done more profitably than our current system. The on-going frequent harvest studies and economic model development should eventually provide an answer to that question. An important part of the economic analysis will be valuation of the ability to apply the robotic platform to other on-farm tasks, particularly weed control.

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