DEVELOPMENT OF SYSTEMS TO IMPROVE COTTON MODULE SHAPE

A Dissertation

by

ROBERT GLEN HARDIN IV

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

August 2009

Major Subject: Biological and Agricultural Engineering

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Approved by:

Chair of Committee,	Stephen W. Searcy
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ABSTRACT

Development of Systems to Improve Cotton Module Shape. (August 2009)

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Properly constructed modules will prevent reduced lint value and increased ginning costs when significant rainfall occurs. Additionally, cotton producers often have difficulty finding adequate labor during harvest. These issues were addressed by developing a graphical operator feedback system, a biomass package measurement system, a powered tramper, and an autonomous module forming system.

A system that provided feedback on the module shape by recording the position of the tramper and carriage was used to direct the operator to move cotton to appropriate locations. The system correctly predicted the height of 67% of data points. Use of the feedback system resulted in a 55% reduction in water collection area of the modules. The module builder operators indicated that the system was useful. The module builder feedback system is a simple, useful, and inexpensive tool that can have a rapid payback for producers.

A powered tramper, with an auger to move cotton to the center of the module, was developed to replace the conventional tramper. The powered tramper operated automatically without affecting the operating speed or pressure of the tramper cylinder.

During testing, the powered tramper was observed moving cotton to the center and crowned modules were produced.

A biomass package measurement system was developed to record the height at multiple points on the top surface of modules. The system was found to produce repeatable measurements with an error of 5 cm. Data collected with this system did not indicate a difference in module shape when using the powered tramper; however, during these tests the powered tramper was turned off prematurely due to an improperly sized valve on the module builder.

An automated module building system capable of both moving and tramping cotton was developed. This system utilized the feedback system sensors and photoelectric sensors to determine the location of cotton in the builder. A wireless display allowed the boll buggy operator to control the automatic system. The automatic system constructed modules with 64% less water collection area in an average time of 37.4 min. Cotton producers indicated that the system was easy to use and of significant value in reducing labor requirements.

DEDICATION

To my wife, Jamie

ACKNOWLEDGEMENTS

This work would not have been possible without the support and assistance of many people. I would like to thank my committee chair, Steve Searcy, for his advice and guidance while completing this research. My other committee members, Robert Lemon, Calvin Parnell, and Alex Thomasson, also provided useful input.

Many other people in the Biological and Agricultural Engineering Department contributed to this work. A number of student workers and shop personnel helped with fabrication and testing of the systems designed in this research. I am grateful to many people in the cotton industry who have supported this research. Development of these systems would not have been possible without the assistance of many cotton producers and ginners.

I would also like to thank my family and friends for their support and patience as I have completed my PhD. My experiences growing up on a dairy farm are what motivated me to become an agricultural engineer. My parents and teachers also encouraged my interest in science from an early age.

Last, and most importantly, I would like to thank my wife, Jamie, for her love and patience as I have finished my dissertation. I know it hasn't been easy for her since I have been traveling for research or working on my dissertation since we got married, yet she has patiently waited on me. I look forward to completing this chapter of our lives and moving to the next together.

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1. INTRODUCTION

The increasing difficulty and cost of obtaining suitable labor to support cotton harvest operations has resulted in a need for harvest systems that can operate with few personnel. The conventional cotton harvesting and storage system, utilizing harvesters, boll buggies, and module builders, requires a large number of seasonal laborers and has remained unchanged since the 1970's. Recently, cotton harvesters with on-board module builders have been developed as a means to reduce labor costs.

However, these harvesters with on-board module builders have several drawbacks, most notably requiring investment in an expensive, specialized machine. The on-board module builders are only available on pickers and will not be viable alternatives for many producers using strippers. A significant portion of the Texas cotton crop, primarily in the High Plains, is harvested by strippers. The modules built by the on-board module builders differ in size and shape from conventional modules, requiring additional or modified equipment to transport and process the modules at the gin.

Preserving cotton quality during storage is important to both producers and ginners. With a decline in the number of gins (Simpson et al., 2004), the length of the ginning season and the length of time that cotton modules are exposed to inclement weather has increased. To maintain cotton quality during storage, modules must be constructed with a shape that does not collect water. Research has demonstrated that the

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This dissertation follows the style of *Transactions of the ASABE.*

economic loss due to poor module shape is over $200 per module, regardless of cover quality (Simpson and Searcy, 2005). Currently, producers generally rely on low-skilled labor to build modules. The module builder operators must quickly distribute and compress the cotton in the module builder due to the large capacities of modern harvesting equipment. These factors make consistent production of high quality modules difficult.

The primary goals of this research are to reduce labor costs during cotton harvesting and maintain cotton quality during storage. Modules must be built with a crowned surface to shed water. Previous research (Hardin IV and Searcy, 2008) has indicated that more cotton must be placed in the center of the module to produce a crowned surface. Seed cotton was compressed in a cylindrical chamber, and the only factor significantly affecting the final recovered height of the column of seed cotton was the mass of cotton compressed. Module builder operators commonly believe that additional compressions can be done to produce a crowned module; however, this research demonstrated that there was little effect from these additional compressions.

A greater mass of cotton is required along the centerline of the module to produce a crowned shape. Cotton should be moved both longitudinally (from the ends to the center) and laterally (from the sides to the center) to produce an optimum module shape. Currently, the operator uses the tramper to push cotton longitudinally in the module builder, relying solely on his judgment and experience to properly distribute the cotton. No mechanical device exists to move cotton laterally. Any movement of cotton in this direction must be done manually. Systems are currently available that will automatically compress the cotton at regular intervals in a module. However, an operator is still required to distribute cotton in the module builder.

1.1. OBJECTIVES

This research has focused on preserving cotton quality during storage by developing systems to produce improved module shapes. Another goal of this study has been to reduce labor requirements through automation. The specific objectives addressed to meet these goals were:

- Develop and evaluate a system that provides information about module shape to assist the module builder operator in constructing modules with improved shapes.
- Design a compressed biomass package measurement system.
- Design and evaluate the effectiveness of a mechanism to move cotton from the sides to the center of the module builder.
- Develop and implement an autonomous module forming system.

The improvements to the module builder resulting from this research will result in improved cotton quality and significant reductions in labor requirements. The basic design of the cotton module builder has remained unchanged for over 30 years, despite increases in yields and harvesting rates. While manufacturers have developed harvesters with on-board module builders, these do not address all industry needs. Retrofitting existing equipment to improve cotton quality or reduce labor requirements may be a more profitable choice for some producers.

Additionally, this work will advance concepts of automation in agricultural production. Automating the tasks performed by machinery has become increasingly important to maintaining profitability in agriculture, as farmers attempt to increase productivity while reducing labor.

This second section of this dissertation contains a review of literature related to the handling and storage of seed cotton. The next four sections are journal manuscripts that each address one of the objectives listed above. The final section contains overall conclusions and recommendations for this research.

2. LITERATURE REVIEW

2.1. SEED COTTON HANDLING AND STORAGE

Adoption of the mechanical cotton harvester resulted in much higher harvesting rates than ginning rates. Harvested cotton was unloaded into trailers used for both storage and transport to the gin. According to Wilkes et al. (1974), loaded trailers often remained at the gin for three to five days. If all of a producer's trailers were loaded awaiting ginning, harvesting had to be stopped, and yield and quality losses could occur in the cotton remaining in the field. The primary way to increase storage capacity was to purchase more trailers. Inexpensive methods of free-standing storage that maintained lint and seed quality needed to be developed so that storage capacity could be increased without investing in massive quantities of equipment.

This problem was recognized by researchers in the early 1960's. Abernathy and Williams (1961) examined the possibility of baling seed cotton for storage using a hay baler or a gin bale press. Baled seed cotton was stored for two months with no significant decrease in lint quality as long as the moisture content was less than 10%. Taylor and Porterfield (1964) also researched storage of seed cotton by baling with a gin press to densities up to 465 kg m^{-3} (29 lb ft^{-3}). Only bales made from stripper-harvested cotton that had not been field-cleaned and were stored exposed to the environment showed significant moisture penetration and a corresponding decrease in lint quality. The only lint quality factor affected by storage in bales without moisture penetration was staple length, which decreased by 1/64 to 1/32 of an inch.

The primary drawback of using gin presses to store seed cotton in bales was that a large number of trailers would still be required to transport the cotton to the gin. The use of trailers was inefficient because trailers were idle most of the time; baling cotton at the gin does not remove this inefficiency. Trailers may still have had to wait at the gin for unloading and baling, and additional machinery would be required at the gin for this additional handling. Baling and storing on the farm with a hay baler would reduce the equipment requirements for transport; however, the density of these seed cotton bales was only 144 kg m^{-3} (9 lb ft^{-3}), only slightly higher than the density of seed cotton in trailers– 96 kg m^{-3} (9 lb ft^{-3}) (Abernathy and Williams, 1961). Handling these bales would be labor-intensive and a purchasing a hay baler only for baling seed cotton was not a cost-effective solution.

A major advance in on-farm storage of seed cotton was the development of the cotton stacking trailer (McNeal, 1966). When loaded with seed cotton, the trailer bed tilted and the rear gate opened. The front wall of the trailer was driven towards the rear to eject the stack of seed cotton. The stacked seed cotton was stored in turnrows and covered to prevent moisture damage. Further work modified the trailer so that cotton was stacked on pallets that could be winched back on to the trailer for transport to the gin (McNeal, 1967).

An economic analysis was performed to compare handling seed cotton with the cotton-stacking pallet trailer and conventional trailers (McNeal and White, 1970). The stacking trailer produced savings of $1.55 per bale for a 182 ha (450 acre) farm with an average yield of 3.0 bales ha^{-1} (1.2 bales $acre^{-1}$). These savings are due to reduced equipment costs, since 12 trailers were needed with the conventional system. Additional savings were likely from not having to delay harvest if trailers were unavailable. A major disadvantage of this system is that the seed cotton in the stacking trailer had to be tramped manually to maintain the integrity of the stack during handling.

The cotton module system, combining the on-farm storage capability of the cotton-stacking pallet trailer with the benefits of compressing the cotton into denser packages, was developed by Wilkes and Jones (1973). A tractor was used for transport and the power take-off (PTO) and hydraulic connections were used to power the module builder. A tramper spanning the width of the module builder was capable of applying 44.5 kN (10000 lb) compressive force. This force corresponded to an applied stress of 103 kPa (15 psi). The tramper was driven by a rack and pinion and mounted to a carriage that could be moved along the length of the module builder.

Cotton was unloaded into the module builder from the harvester, and the module builder operator used the carriage and tramper to distribute cotton evenly along the length of the module. The tramper was then used to compress the seed cotton in the module builder. Finished modules had a density of 196 kg m^{-3} (12 lb ft^{-3}) (Wilkes et al., 1974).

Early improvements to the module builder included a stronger frame and mounting the transport wheels on a walking suspension beam (Orlando and Hendriks, 1976). A hydraulic cylinder was used by Johnston (1976) to drive the tramper. This cylinder was lowered with a release mechanism for highway transport. A self-propelled module builder was developed by Haney and Orlando (1980) with an engine and drive wheel to eliminate the need for a tractor.

Bass III (1992) designed a carriage that was driven by hydraulic motors directly connected to the carriage wheels. This modification reduced maintenance needs, provided for smoother operation, and increased operator safety by eliminating the drive chains. However, the additional hydraulic components generally increase cost. Another modification of the module builder was replacement of the tramper with a roller (Hewitt and Hewitt, 1998). This roller did not need to be raised and lowered when compacting cotton, resulting in increased speed of operation.

Researchers have recognized the potential benefits of automating the module builder from the time of its introduction. Shelby and Parish (1975) developed an automatic control system for the module builder (figure 2.1). This system used solenoid valves to control the tramper and carriage. Limit switches at the front and rear detect the carriage and change the direction of carriage motion. A pressure switch stopped downward motion of the tramper. Time delay relays were used to control the height the tramper was raised and the distance between successive compression strokes.

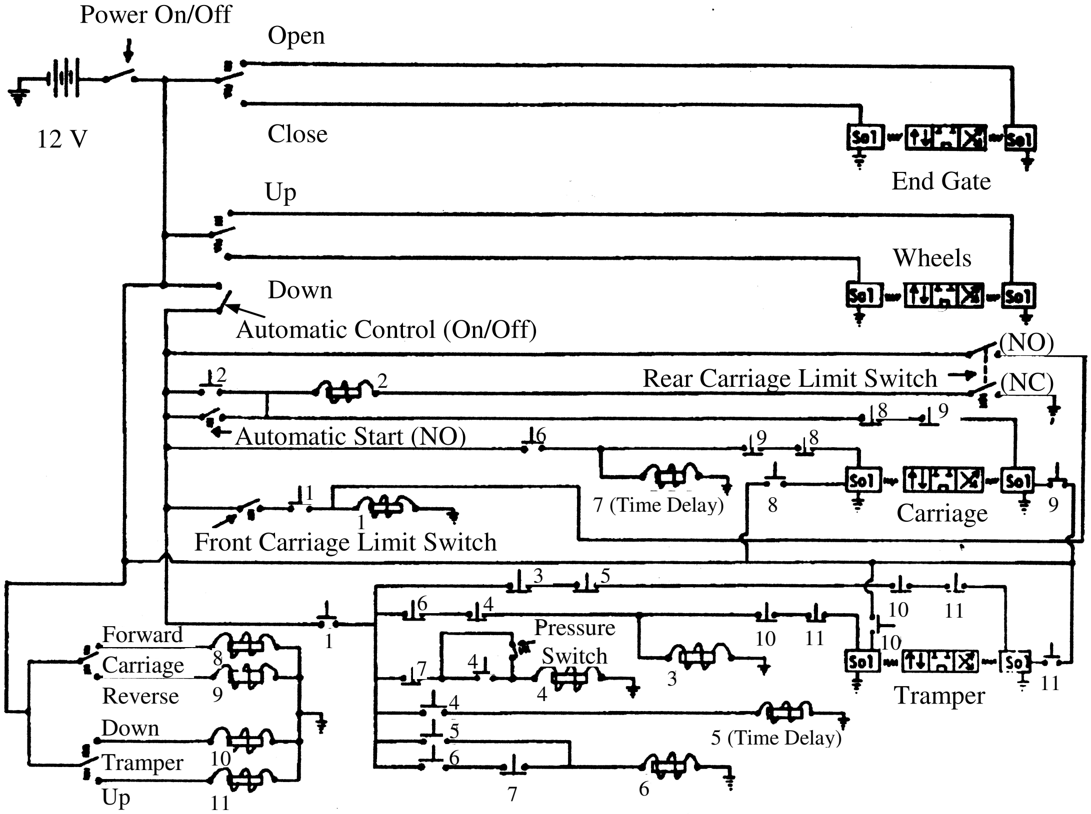

Figure 2.1. Automatic control system electric circuit (from Shelby and Parish, 1975).

Initially, the tramper was set to a desired height for leveling the cotton in the module builder. The automatic system was started, and the carriage moved from the front to the rear. After reaching the rear of the module builder, the automatic system began compaction of the cotton. When the carriage reached the front of the machine, the system stopped.

The leveling action would likely be insufficient in modern module builders. More cotton would accumulate at the rear of the module builder and less cotton would be in the front. Initially, the module builder operator often desires to create a void in the center of the module to facilitate unloading of cotton from a harvester or boll buggy. When completing a module, the operator should move more cotton to the center to create a crowned surface. Finally, cotton often can not be leveled in one pass because the force required is too large and the carriage stalls. Inefficiency existed in the compaction cycle because the tramper may be raised further than necessary.

A different method of automating the compression of cotton in the module builder was designed by Edinburgh (1995). A camshaft with two cams was driven by a hydraulic motor, with the speed controlled by a flow control valve. The cams were connected to control levers on the valves actuating the carriage motor and tramper cylinder. The design of the camshaft and connecting rods resulted in sequential operation of the valves to automate the module builder. The tramper was lowered and raised, followed by movement of the carriage. An automatic or manual switch was provided to change the direction of fluid flow to the carriage motor when one end of the module builder was reached.

Modern module builders are generally similar to the version described by Orlando and Hendriks (1976). Both chain-drive and direct hydraulic drive carriage are available from manufacturers. Module builder dimensions have been standardized by the American Society of Agricultural and Biological Engineers (ASABE) to facilitate handling and transport of modules (2005). The standard module builder has an inside base width of 2.21 to 2.3 m (7.25 to 7.54 ft), a maximum operating height of 3.35 m (11 ft), and a maximum base length of 9.74 m (32 ft). The sides and the ends have an inward taper of 25.4 mm (1 in.) for each 304.9 mm (12 in.) of height. The maximum height of the module forming chamber (not including the portion of the sides extended out at the top) is 2.59 m (8.5 ft).

Automatic tramping systems are available from manufacturers and as a retrofit option. These systems function similarly to the automatic controller described by Shelby and Parish (1975). Downward movement of the tramper is stopped by a pressure sensor and retraction of the tramper and carriage movement is governed by time delays, which can generally be set by the user. Limit switches detect when the carriage has reached the end of the module builder. One automatic system includes a camera, video monitor, and wireless remote to allow the boll buggy operator to control the module builder (Module Automation Systems, 2009). However, no systems available commercially or described in literature have the capability to distribute cotton. An operator is required to distribute the cotton for proper shape and to prevent cotton from being pushed out of the module builder as the module nears completion.

Equipment manufacturers have been interested in developing harvesters with on-board module builders to reduce labor requirements and increase harvesting efficiency. One of the first attempts to develop an on-board module builder was by Fachini and Orsborn (1985). This harvester used a horizontal auger with the basket divided into multiple sections. When the cotton had been compressed significantly in one section, the force of the partially formed module would open the hinged divider, allowing more cotton to be added to the module. The finished module was unloaded from the rear of the harvester. However, this design was never commercialized.

A more recent design of a cotton picker with an on-board module builder, the Module Express 625, has been commercialized by Case IH. This system builds modules of standard width and height that are one-half the length of a conventional module. The design of this system was initially detailed by Covington, et al. (2003a, 2003b). The compaction mechanism consists of a frame with augers that extend along the length of the module forming chamber. Cotton is conveyed to the top of this frame, and falls through to the surface of the partially formed module.

A description of the sequence of distribution and compaction steps is given by Archer et al. (2007). Initially, cotton is compressed by the compactor. The compactor is then raised a given height, so cotton can be leveled. The augers are rotated by hydraulic motors in one direction to distribute the cotton in the module. The direction is determined by calculating the tilt of the compactor frame. When the hydraulic pressure required to rotate the augers increases above a set point or a given time has elapsed, rotation stops and the sequence is repeated. When the module is finished, a rear gate folds down and the module is unloaded.

A different method of building on-board modules has been developed by John Deere, with the 7760 cotton picker. This system builds 2.44 m (8 ft) wide round modules with a maximum diameter of 2.29 m (7.5 ft). This on-board module builder functions similarly to a round hay baler (Gola et al., 2000; Deutsch et al., 2001). An accumulator receives cotton from the picking units. A mat of cotton is formed and fed to a round baler. The finished round module is covered with plastic wrap and unloaded from the module chamber. The picker has the capability to carry one finished module to the end of the row.

One major drawback to the commercial on-board module builders is that they are only available on pickers. A significant amount of cotton, primarily in the Texas High Plains, is stripper harvested– 23% of U.S. cotton and 85% of Texas cotton in the 1994-95 harvest season (Glade et al., 1996). Recently, pickers have been used more frequently in the Texas High Plains with higher-yielding varieties under irrigation. Regardless, a significant portion of Texas and U.S. cotton is still stripper harvested.

Stripper harvested cotton is generally lower yielding and has a lower cost of production than picker harvested cotton. For this reason, many producers using strippers are not likely to switch to a picker, even if it has an on-board module builder. Faulkner et al. (2009) conducted an economic analysis comparing picker and stripper harvesters in the Texas High Plains. With 324 ha (800 acres) harvested per machine, stripping was more profitable with yields less than 5.75 bales ha^{-1} (2.33 bales $acre^{-1}$). As the area harvested per machine increased, the breakeven yield decreased. However, even with 647 ha (1600 acres) harvested per machine, the breakeven yield was still 3.1 bales ha^{-1} (1.25 bales $acre^{-1}$). Stripping will likely be more profitable for dryland production in the Texas High Plains. These producers have no option other than using boll buggies, module builders, and the required support labor.

Another issue regarding the commercial on-board module builders is the quality of module shapes produced. Case IH has made attempts to produce modules with a crowned shape. One implementation arranged the augers in a concave arc; however, this will not move more cotton to the center (Orsborn and Covington, 2005). This design is similar to the use of arched trampers in conventional module builders, which have not been shown to produce more desirably shaped modules. A subsequent design used augers with opposite-handed flighting to attempt to move cotton across the width of the module, but no data is currently available on the likelihood of these modules to collect water (Dupire et al., 2006). Because the Deere modules are round, there is no potential for water to collect on the top surface of the modules. However, observation of some round modules indicated that water could enter the module through tears in the plastic and collect at the bottom of the module.

The round modules also require different equipment for handling and ginning. Producers need an implement to move the modules from turnrows to a central area on the farm. The modules can be transported with a conventional module truck; however, the chains in the truck bed must be replaced. The gin requires special equipment to unwrap the modules and must handle large quantities of the plastic wrap. Modifications to the module feeder may also be needed.

Another design for an on-board module builder that could be suitable for stripper harvesters has been described by Lackey (2008), although this design has not been produced commercially. A wheeled frame is towed behind a cotton harvester with no conventional basket. The cotton is conveyed from the picking units into a holding chamber on the towed frame. This compaction chamber consists of a fixed top, bottom, and sides. The rear of the chamber consists of a movable wall. A horizontal compactor compresses cotton against the movable wall. As additional cotton is added, the wall moves towards the end of the module builder, essentially constructing a module using a slip form. When the module is completed, the frame is tilted and the module unloaded off the rear.

While this module builder could be used with a stripper harvester, significant modification of the harvester would be required. The quality of modules that could be built with this system is unknown. When initially forming the module, the compressed cotton may not maintain its integrity as it leaves the slip form. Additionally, there are no means for producing a crowned surface.

The increasing cost and difficulty in finding labor for cotton harvesting has led to the development of these on-board module builders. However, no equipment has been developed for producers using stripper harvesters. The harvesters with on-board module builders cost approximately $100,000 more than conventional pickers and $300,000 more than strippers (Mississippi State University Department of Agricultural Economics, 2009). Labor-saving systems that can be retrofit to existing equipment may be more economical for some producers.

2.2. EFFECTS OF MOISTURE ON SEED COTTON QUALITY

Preserving seed cotton quality during storage is important to both producers and ginners. High moisture content of stored seed cotton is the primary factor that will decrease lint and seed quality. Excess moisture provides a favorable environment for microbial growth, which degrades the cottonseed. A common indicator of modules with high moisture content is the increased temperature that occurs as a result of the microbial activity.

Griffin (1975) found that cottonseed stored with seed moisture levels greater than 16% had a significant decrease in quality, with germination rates less than 50%. Moisture content also negatively affected the milling grade index, a measure of seed quality when used for oil. Seed cotton that was picked before the dew evaporated and stored had an index of 84.1, compared with values of 95.1 and 96.6 for cotton that was picked wet and dried before storage and cotton that was picked when dry. In laboratory tests, Wilkes (1978) determined that cotton with seed moisture levels less than 10% could be stored for at least 30 days with no decrease in seed quality. Increasing seed moisture levels resulted in decreasing safe storage times. Comparable results were found in modules, with a maximum 11% seed moisture content for safe storage. This seed moisture content occurred when the average seed cotton moisture content was 10%. Curley et al. (1988) found that germination decreased when the seed cotton moisture level in the module was between 13 and 16% and stopped when the moisture level rose above 16%.

The degradation of cottonseed discolors the lint, resulting in less desirable color grades. In testing different baling methods for seed cotton, Abernathy and Williams baled cotton at three different moisture contents and stored the bales for three weeks. The seed cotton was classified as low (average moisture content of 10%), medium (13%), or high (15%) moisture. The higher moisture levels significantly decreased the USDA color grade index and had higher colorimeter yellowness (+b) values. The higher yellowness value corresponds to a larger second number in the USDA color grade, for example moving from a 31 to a 32, and a decreased lint value.

Parish and Shelby (1974) observed a significant decrease in lint quality when the seed cotton moisture content in a module exceeded 18%. Temperatures above 43°C (110°F) indicated a decrease in lint quality. Griffin found that a similar moisture content also resulted in lower lint grades, when compared to cotton picked dry. Curley et al. also found similar results, as yellowness began to increase significantly at a moisture level of 13 to 14%.

Based on the results of these researchers, the maximum safe moisture content for storage of seed cotton is approximately 12%. Increasing the moisture content above this level results in increased yellowness, less desirable color grades, and decreased lint value. Researchers have generally agreed that modules need to be built with a crowned surface that sheds water. Willcutt et al. (1992) indicated that moisture damage to stored seed cotton was a serious problem, caused partly by poorly shaped modules. Brashears et al. (1993) indicated that depressions in the module surface were responsible for the failure of a spray-on cover. Higher areas of the module surface had lower moisture contents, but the water was channeled into depressions, where moisture damage occurred.

Simpson and Searcy (2005) calculated the economic cost of poorly shaped modules due to decreased lint value. Regardless of cover quality, a poorly shaped module that experienced significant rainfall lost an average of $200 in lint value when compared to a properly crowned module. Additional economic costs are incurred by ginners, as wet cotton is ginned at a significantly lower rate. Previous work by Simpson and Searcy (2004) indicated that 50% of modules surveyed in Texas gin yards showed evidence of ponded water or areas where water could potentially collect.

Clearly, poorly shaped modules will have decreased lint value if exposed to significant rainfall. A properly constructed module depends on the operator visually observing the level of cotton in the module builder and using the tramper to longitudinally move cotton. This task is often difficult for inexperienced operators to accomplish efficiently, and made more difficult when operating at night or moving cotton at the far end of the module builder. Furthermore, cotton can only be moved laterally if a person enters the module builder and physically moves the cotton (figure 2.2). Manually moving cotton is inefficient and potentially dangerous. Systems that aid the operator in moving cotton or convey the cotton automatically towards the center could significantly improve module shapes, increasing profits for farmers and ginners.

Figure 2.2. Workers waiting on cotton to be unloaded so they can manually distribute the cotton in the module builder.

2.3. PHYSICAL PROPERTIES OF SEED COTTON

Constructing properly shaped modules and designing seed cotton handling equipment requires an understanding of the physical properties of seed cotton. Predicting the module shape resulting from a given sequence of operator actions requires knowledge of the relationship between the applied force, deformation, and time-dependent recovery.

Brashears et al. (1970) investigated the relationship between applied pressure and density in seed cotton. Seed cotton was compressed to a density of 481 kg m^{-3} (30 lb ft^{-3}) and recovered to 320 kg m^{-3} (20 lb ft^{-3}), indicating significant inelastic deformation. This inelastic deformation allows free-standing modules to be constructed; however, the compressed density used in the experiment was much greater than densities reached in module builders. Seed damage occurred at this density at lower moisture levels.

To more accurately predict seed cotton behavior in a module builder, Hardin IV and Searcy (2008) examined the viscoelastic properties of seed cotton with lower applied forces and compressed densities. Seed cotton samples were compressed in a cylindrical chamber with easily removed walls for measurement of recovery without the effect of wall friction. The effects of the initial loading density, number of compressions, time the compressive force was applied to the seed cotton, harvest method (picked or stripped), and the loading method (entire mass at once or one-half initially and one-half after the first compression) were tested in a partial factorial design. Moisture content was also measured and used as a covariate in the statistical analysis.

Hardin IV and Searcy (2008) discovered that with a constant compressive force, a similar compressed density was achieved regardless of the initial density or mass of seed cotton. The mass of seed cotton being compressed was the primary factor affecting the final recovered height. The implication of this work in constructing modules was that a cotton module will have a similar final density at various locations along the width and length of the module, since the tramper supplies a constant force. If the mass of seed cotton is distributed unevenly throughout the module, the height will vary across the module, and the top surface will be uneven. A greater mass of cotton needs to be located along the centerline of the module to produce a crowned shape. The compressed height of the cotton under the tramper is a useful predictor of the mass of cotton at that point in the module builder. These findings indicated that the common practice of repeatedly tramping higher areas of the module is ineffective. The cotton may appear to have a level or crowned appearance in the module builder, but expansion after the module builder is removed will result in an uneven surface.

This study also found that picker harvested cotton was compressed to a greater density than stripper harvested cotton; however, the final recovered densities were similar. Multiple compressions increased the density of the seed cotton, but the effect was not physically significant after the third compression. Seed cotton in a module builder only needs to be compressed until there is no loose, uncompressed cotton remaining on the surface. The compressed density of the seed cotton increased by 5 kg m^{-3} (0.3 lb ft^{-3}) for every 1% increase in moisture content. Creep loading was not a practical method of increasing density because the time-dependent deformation was small relative to the instantaneous deformation.

Mathematical models of the compression and creep data from this experiment were developed by Hardin IV and Searcy (2009). The physical model used to describe the data was originally developed by Bilanski and Graham (1984) (figure 2.3).

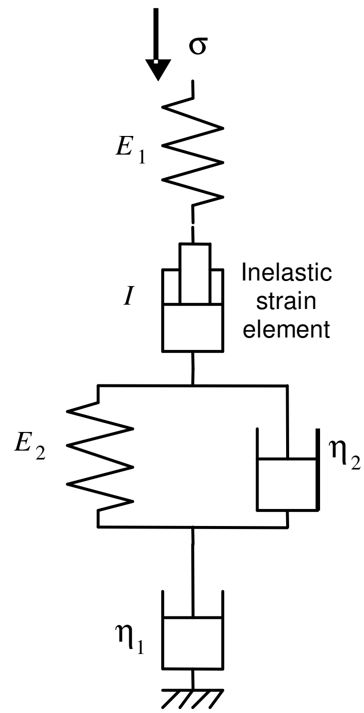

Figure 2.3. Viscoelastic model developed by Bilanski and Graham.

Compression of the seed cotton was described by the following equation:

$$\left(\frac{\gamma_0}{\gamma}\right)\left(\frac{\gamma_{\max}-\gamma}{\gamma_{\max}-\gamma_0}\right) = e^{-\frac{\sigma}{K}} \tag{2.1}$$

where

γ_0 = initial density (kg m^{-3})

γ = measured density (kg m^{-3})

γ_{max} = asymptotic maximum density (kg m^{-3})

σ = applied compressive stress (Pa)

K = combined modulus of elasticity and plastic strain constant (Pa).

This equation was derived by using a height ratio to calculate the logarithmic, or true, strain and replacing the height ratio with an equivalent density ratio. The parameters γ_{max} and K were determined using a nonlinear regression procedure.

The density-time relationship for seed cotton was developed from the equations of motion for the various components in the model, using the true strain. This relationship was given by the following equation:

$$\ln\left(\frac{\gamma}{\gamma_c}\right) = \sigma_0\left(\frac{t}{\eta_1} + \frac{1}{E_2}\left(1 - e^{-\frac{E_2}{\eta_2}t}\right)\right) \tag{2.2}$$

where

γ_c = density at start of creep loading (kg m^{-3})

σ_0 = constant applied stress during creep loading (Pa)

t = time (s)

η_1 = viscosity of series-connected damper (Pa s)

E_2 = modulus of elasticity of parallel-connected spring (Pa)

η_2 = viscosity of parallel-connected damper (Pa s).

These models accurately described the behavior of seed cotton, with an average R^2 value of 0.924 for the compression model and an average R^2 of 0.999 for the creep model. The density of seed cotton initially increased rapidly as a compressive force was applied, but the force increased exponentially. This constraint imposes practical limits on the density attainable for storing seed cotton. The model accounted for the significant inelastic deformation of seed cotton from the compression of void spaces.

2.4. SUMMARY

A significant number of workers are currently required to harvest cotton. Due to inexperienced operators and the speed of modern harvesting operations, cotton is frequently not properly distributed in the module. The resulting modules will have depressions in the top surface where water could potentially collect, significantly reducing lint and seed quality. The development of systems to aid operators in moving cotton longitudinally and laterally can improve operator productivity and produce module shapes that prevent water collection and quality loss.

Cotton pickers with on-board moduling capabilities have recently been developed. While these pickers significantly reduce labor requirements for cotton harvesting, some producers may be better served by other technologies. An automated module forming system could be used by producers with cotton strippers to significantly decrease labor costs. This system could also be retrofit to existing module builders, reducing labor requirements without the significant capital investment required for the cotton pickers with on-board module builders.

3. OPERATOR FEEDBACK SYSTEM

3.1. INTRODUCTION

Maintaining seed cotton quality during storage is a serious concern for producers and ginners. Serious economic losses can result from moisture damage to seed cotton in modules. If significant rainfall occurs, the degree of quality loss is affected by the condition of the module cover and the shape of the module. Quality loss occurs when rain collects in depressions on top of the module and leaks through the cover. Module covers are designed to resist water penetration, but the covers actually used are often damaged. Weathering and rough handling of the covers over several years of use reduces the resistance of the cover material to water and creates holes, allowing water to leak into the cotton.

Module shapes that shed water are critical to maintaining cotton quality during storage, since many covers will allow penetration of collected water. To properly construct a module, the operator must use the tramper to move cotton from areas with more mass into regions with less cotton. Several factors complicate this process. It is difficult to visually estimate the mass of cotton in a particular location in the module, as certain regions may not have been compressed. The module builder operator may also have difficulty seeing the far end of the module builder. Therefore, a system that provides information about module shape to the operator should result in modules that do not collect water and produce higher quality lint and seed.

3.1.1. Objectives

This research was conducted as part of a larger project to improve post-harvest handling of seed cotton. The primary goal of this specific project was to develop a system that provides information about module shape to the module builder operator. Modules should be built with a convex (outwardly sloping) surface to shed water. Since the operator can move cotton along the length of the module builder, this feedback system should indicate the predicted height of the module along its length. Using this information, the operator could move cotton to the appropriate areas to produce a module with a convex shape. The objectives of this research project were:

- Design a system to provide the operator an image of the predicted module shape based on the operator's actions.
- Evaluate the accuracy of this system in predicting module shape.
- Evaluate the usefulness of the system to operators and its effectiveness in improving module shapes.

3.2. LITERATURE REVIEW

The module builder has been largely unchanged since its introduction by Wilkes and Jones (1973). The improved frame and transport wheel design by Orlando and Hendriks (1976) and the use of a hydraulic tramping cylinder (Johnston, 1976) have been incorporated in commercial designs. The chainless carriage drive, originally designed by Bass III (1992) is offered as an option by module builder manufacturers. Automatic control systems similar to the original design by Shelby and Parish (1975) are also widely used in industry. These systems do not include algorithms for distributing the cotton, requiring an operator to perform this task. Therefore, these systems can reduce labor, but the module shape remains solely dependent on the skill of the operator.

The economic loss due to a poorly formed module has been estimated at over $200/module if rainfall occurs, regardless of cover quality (Simpson and Searcy, 2005). Therefore, modules must be built with a shape that prevents the collection of rainwater. However, a survey of Texas gins found that 50% of modules had depressions with evidence of water collection or the potential to collect water (Simpson and Searcy, 2004).

A study of the physical properties of seed cotton (Hardin IV and Searcy, 2008) concluded that more cotton must be placed in the center of the module to produce a convex top surface. Additional compression of high areas will not significantly affect the module shape. To properly construct a module, the operator must move cotton from areas with more mass into regions with less cotton. Several factors complicate this process. It is difficult to visually estimate the mass of cotton in a particular location in the module, as certain regions may not have been compressed. Visibility is reduced when operating at night or at the far end of the module. Therefore, a system that provides information about module shape to the operator should result in modules that do not collect water and produce higher quality lint and seed.

The 2008 study by Hardin IV and Searcy also demonstrated that with a constant force, the compressed height of seed cotton varies linearly with the mass of cotton compressed. The final recovered height deviated slightly from this linear relationship with the mass of seed cotton, as the greater weights of seed cotton resulted in additional compression. However, this effect was slight over a large range in masses– 4.1 kg to 8.2 kg. Since this effect was small and the range of masses encountered at different locations in the module builder will likely be smaller than the range used for testing, measurements of the compressed height of seed cotton were used as the basis for the feedback system. The minimum height during a tramping stroke was used as the indicator of the mass of cotton at that location in the module and consequently, the resulting height of the finished module.

3.3. MATERIALS AND METHODS

3.3.1. Design

The operator feedback system should accurately predict the shape of the module. This system needs to be inexpensive and easily retrofit to existing module builders to facilitate its adoption by cotton producers. The feedback system also should be simple to use and provide information to the operator in an easily understood format.

Accurate prediction of module shape requires knowledge of the relative mass at different positions along the length of the module (Hardin IV and Searcy, 2008). This information will guide the operator in distributing cotton from regions of greater mass to areas of lower mass in the module builder to avoid depressions in the module surface. The compressed height of seed cotton was found to be linearly proportional to the mass of seed cotton. Therefore, measuring the minimum height of the tramper during compression provides information about the mass of cotton at that location in the module builder and can be used to predict module shape.

Determining the minimum height during a compression action required knowledge of the carriage and tramper position. Sensors were installed on the module builder to record the position of these elements. Tramping strokes had to be differentiated from leveling actions performed by the operator. A microcontroller was used to process the sensor data and control an LCD display of the module shape.

3.3.1.1. Hardware

The tramper position was determined using an ultrasonic sensor (SensComp MINI-AE*) due to its low cost and adaptability. The tramper sensor was installed on the carriage and detected a target plate mounted on top of the tramper support column. This sensor produced an analog output of 0-5 V over a range of 15.24 cm (6 in) to 304.8 cm (10 ft). The resulting tramper height resolution of the feedback system was 1.14 cm.

Originally, an ultrasonic sensor was used to determine carriage location; however, the carriage position could not be adequately sensed (Hardin IV and Searcy, 2006). The ultrasonic sensor was not accurate over the full range of carriage motion due to misalignment of the sensor and target area, wind, and dust. As a result, a different sensing technique was used for determining the carriage location. Two 18 mm diameter inductive proximity sensors (Automation Direct AK1-AN-3H) were used to track

*Brand names are provided for informative purposes and their use does not constitute an endorsement of any product.

carriage motion (figure 3.1). The sensors were mounted on the channel at the front of the module builder and detected a hub mounted on the carriage drive shaft. The sensing hub consisted of four steel teeth welded to each side of a split shaft collar. Each time a tooth passed the sensor, a pulse was produced. Counting the number of pulses indicated the distance the carriage had moved- 9.53 cm (3.75 in.) per pulse. The two sets of teeth were offset approximately 12° so that the direction was determined by comparing the values from the two sensors. The sensor mount was adjustable so the distance between the sensors and the hub could be set precisely.

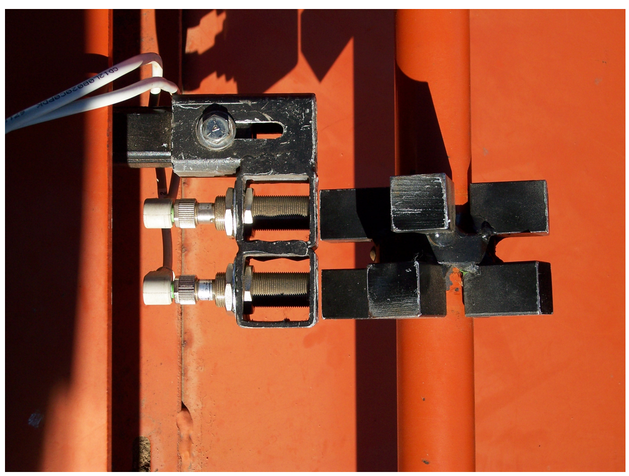

Figure 3.1. Carriage position sensing apparatus.

Thirty mm inductive proximity sensors (Pepperl+Fuchs NBB10-30GM50-E2-V1) were also used to provide an absolute position reference for the carriage. These sensors detected when the carriage reached the front or rear of the module builder, preventing any position errors from accumulating. The feedback system was installed on a module builder that already had these sensors as part of an automatic tramping system.

The module shape was displayed on a graphical LCD. An 8-bit microcontroller, the Motorola 68HC11, was used to process the sensor data and control the LCD. The LCD, microcontroller, and other electronics were contained in an enclosure mounted in the cab of the module builder (figure 3.2). Several controls were provided for the operator – power switch, reset, LCD contrast adjustment, and LCD backlight switch.

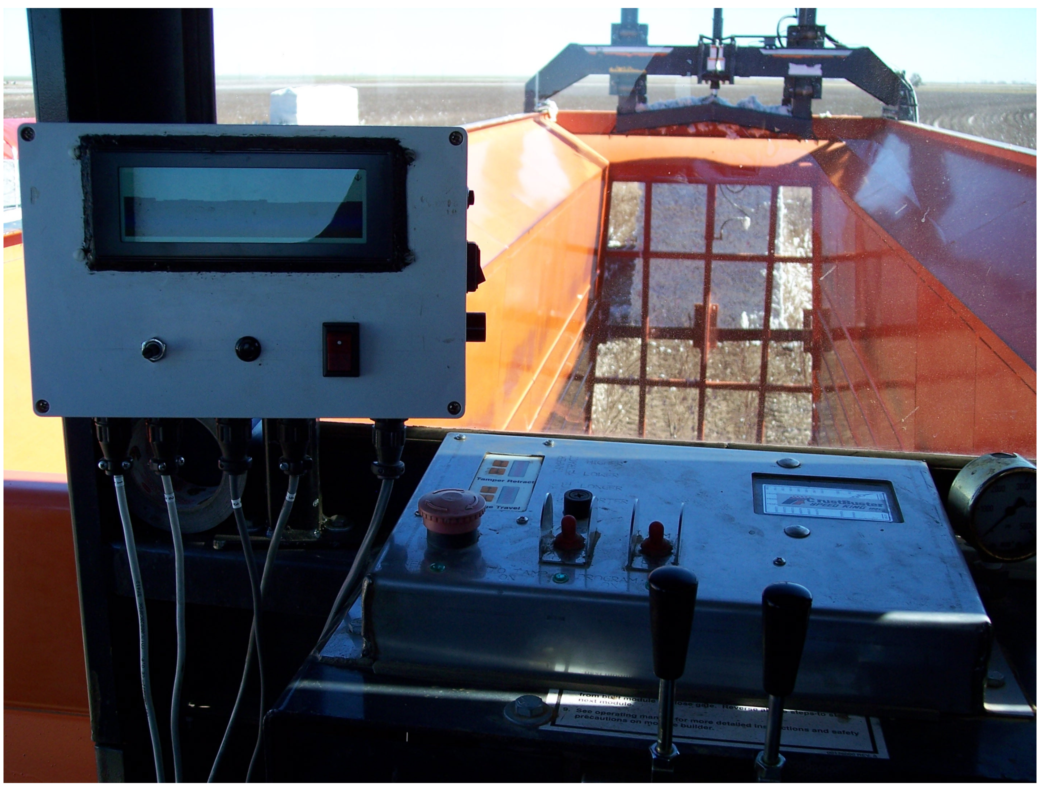

Figure 3.2. Feedback system (upper left) mounted in module builder cab.

3.3.1.2. Algorithm

The feedback system must identify tramping strokes, since the compressed height of cotton is proportional to the mass. The algorithm identified a tramping stroke when the tramper moved down and back up a minimum distance while the carriage was stationary. To correctly identify tramping strokes, the algorithm needed accurate readings of the carriage and tramper locations.

One carriage position sensor was used to generate a microcontroller interrupt. When the interrupt occurred, the value of the other sensor was read to determine if the carriage location should be incremented or decremented. The front and rear proximity sensors also generated interrupts, which set the carriage location to the minimum and maximum values, respectively. Therefore, the carriage location was continuously updated, and the algorithm could access the value when necessary.

Preprocessing of the tramper sensor values was done to improve accuracy. The ultrasonic sensor measuring tramper height was converted to a digital value using the 8-bit analog to digital converter on the microcontroller. The digital output was smoothed using an exponential moving average with a smoothing factor of 0.4, calculated by the following formula:

$$Y_t = \alpha X_t + (1 - \alpha) Y_{t-1} \tag{3.1}$$

where

Y_t = current smoothed value

α = smoothing factor

X_t = current tramper sensor value

Y_{t-1} = smoothed value from previous observation.

The exponential moving average was rather simple to implement in the feedback system program, since only the last smoothed value had to be stored due to the recursive nature of the smoothing algorithm. Based on observation of preliminary data collected with the feedback system, a smoothing factor of 0.4 was selected to provide acceptable smoothing without introducing a long time delay in the smoothed signal.

Both carriage and tramper locations were compared to minimum and maximum values to eliminate physically impossible values. Outlier detection was also implemented, since the speed of carriage and tramper movement was limited. The carriage location and the tramper sensor value were read by the feedback system program every 0.1 s. If the carriage location had changed by more than a carriage movement threshold since the previous reading, the carriage location was reset to the previous reading. The tramper sensor value was compared to the smoothed sensor value calculated after the previous reading. If the difference in these values was greater than the tramper movement threshold, the tramper sensor reading was ignored and the smoothed sensor value was not updated. These movement thresholds were set in the program software.

Figure 3.3 details the algorithm for determining the occurrence of a tramping stroke. At every sensor reading, the position of an arrow on the LCD screen indicating the carriage location was updated. A compression stroke only occurred while the carriage was stationary. As a result, the system polled the tramper sensor when carriage movement stopped.

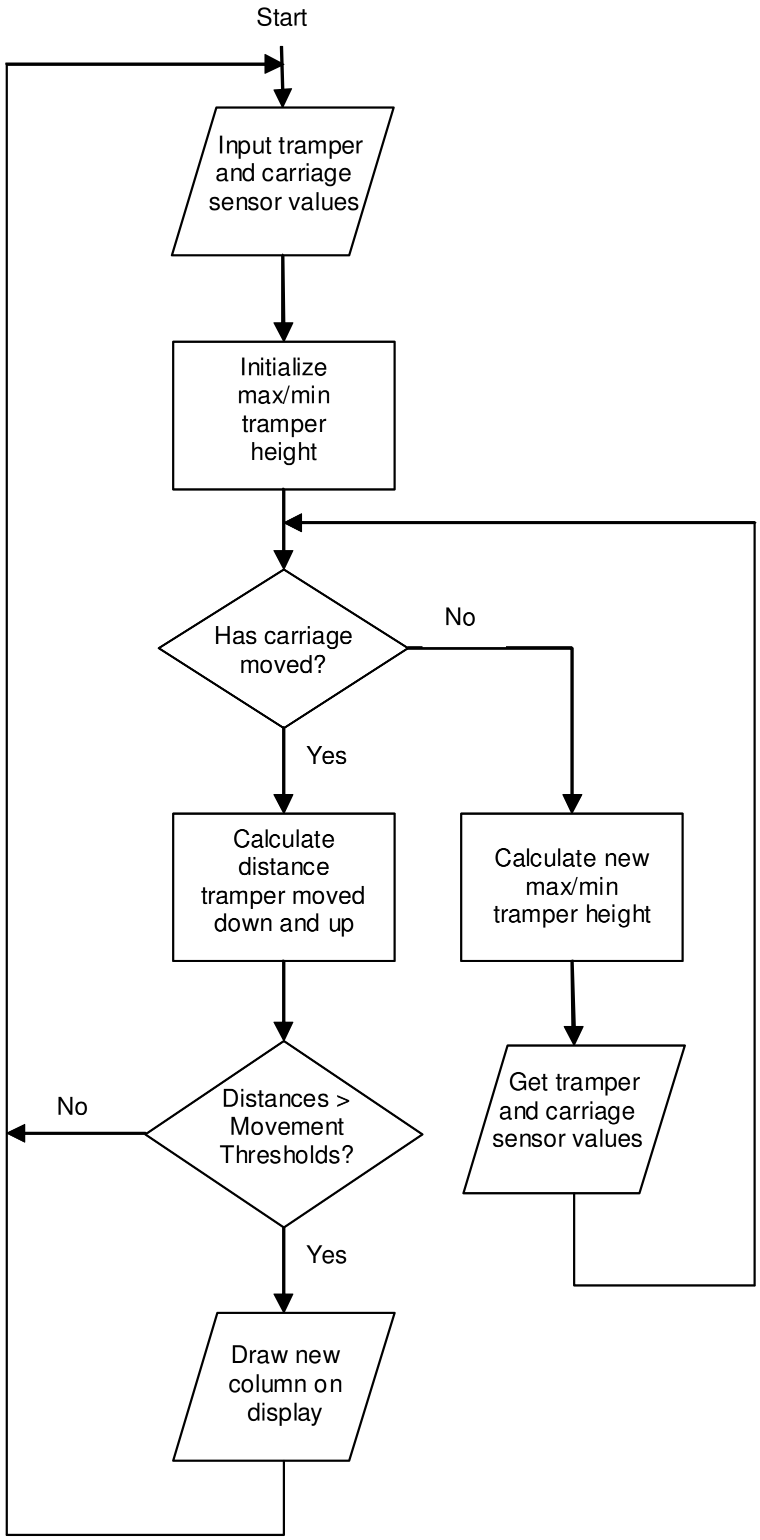

Figure 3.3. Feedback system algorithm flowchart.

Three values were identified with the carriage stopped– the maximum height of the tramper before the compression stroke, the minimum compressed height, and the maximum height after compression. These values were used to calculate the distance the tramper moved, which was compared to a threshold distance of 29.1 cm to 43.5 cm. This threshold varied inversely with the minimum compressed height, since the operator generally does not have to raise the tramper as high to clear the cotton adjacent to the tramper as the module nears completion.

When the system determined a tramping stroke had occurred, a column was displayed at the appropriate location on the LCD screen. The screen was divided into 30 columns, 8 pixels wide; therefore, each column corresponded to 29.21 cm (11.5 in) of carriage movement. The height of the column was directly proportional to the minimum compressed height– each additional increment in column height corresponded to an increase in the minimum compressed height of 2.85 cm (1.12 in). Figure 3.4 shows the display of a finished module, with the carriage at the rear of the module builder. When starting a new module, the operator pressed the reset button to clear the display. Electrical schematics and circuit board layouts of the feedback system electronics are shown in appendix A.

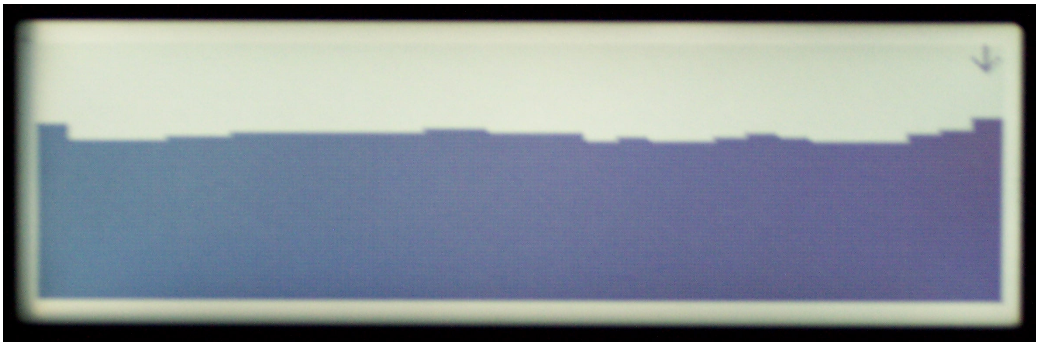

Figure 3.4. Feedback system display.

3.3.2. Testing

The feedback system was installed in November 2006 on a module builder in the High Plains of Texas. The harvesting crew that used the feedback system had almost no experience building modules. Originally, the system was installed in a location where the operators could not see the display. The quality of the modules built without the system was evaluated. The system was then mounted inside the cab (figure 3.2) where it could be used by the operator. The original testing plan involved each operator using the module builder with the system installed where it was not visible and later with the system in the cab. Due to weather and mechanical problems with the module builder, this plan was not fully implemented. A total of 12 modules were built using the system, under the conditions described in table 3.1.

Table 3.1. Module test conditions.

Module #	Operator	Display Visible?
1	A	No
2	A	No
3	A	No
4	A	No
5	A	No
6	B	Yes
7	B	Yes
8	B	Yes
9	B	Yes
10	B	Yes
11	A	Yes
12	A	Yes

The feedback system was equipped with a data collection system. At every sensor reading (0.1 s intervals), a status byte, time stamp, and the sensor values were transmitted over the microcontroller's serial communications interface to a Bluetooth serial port device. When the algorithm determined that the carriage had moved, a status byte indicating whether a display occurred, a time stamp, the carriage position, the minimum tramper height, the maximum starting tramper height, and the maximum ending tramper height were all transmitted to the Bluetooth device. The data was collected wirelessly for further analysis using a Bluetooth-enabled laptop. The information collected was used to determine the final height of the module predicted by the feedback system. The data was also analyzed to determine the accuracy of the system in identifying compression strokes. Compression actions were identified manually and the algorithm's performance evaluated.

The actual module height was also measured for the 12 modules in table 3.1. Height measurements were taken at the front of the module, every 91.4 cm (3 ft) from the front of the module, and at the rear of the module, resulting in 12 height measurements. The height measurements were taken by placing a measuring tape over the top of the module and recording the distance from the ground on one side of the module to the ground on the other side. The actual height was estimated by subtracting 2.13 m (7 ft) from the measurement (for the top width of the module) and dividing by two. This method was used because it was faster and more accurate than measuring the actual height and two people could make the measurements from the ground. The estimated actual height was compared to the final displayed column height to determine the system accuracy in predicting module height.

Five additional modules built by operator B before he used the feedback system were also measured. These modules were compared to the 5 he built using the system to determine if the feedback system had any effect on module shape. To provide an objective assessment of module shape, the size of the areas in the module profile where water could collect was calculated. Figure 3.5 provides an example of this calculation. The areas covered by the diagonal black lines represent areas where water could collect.

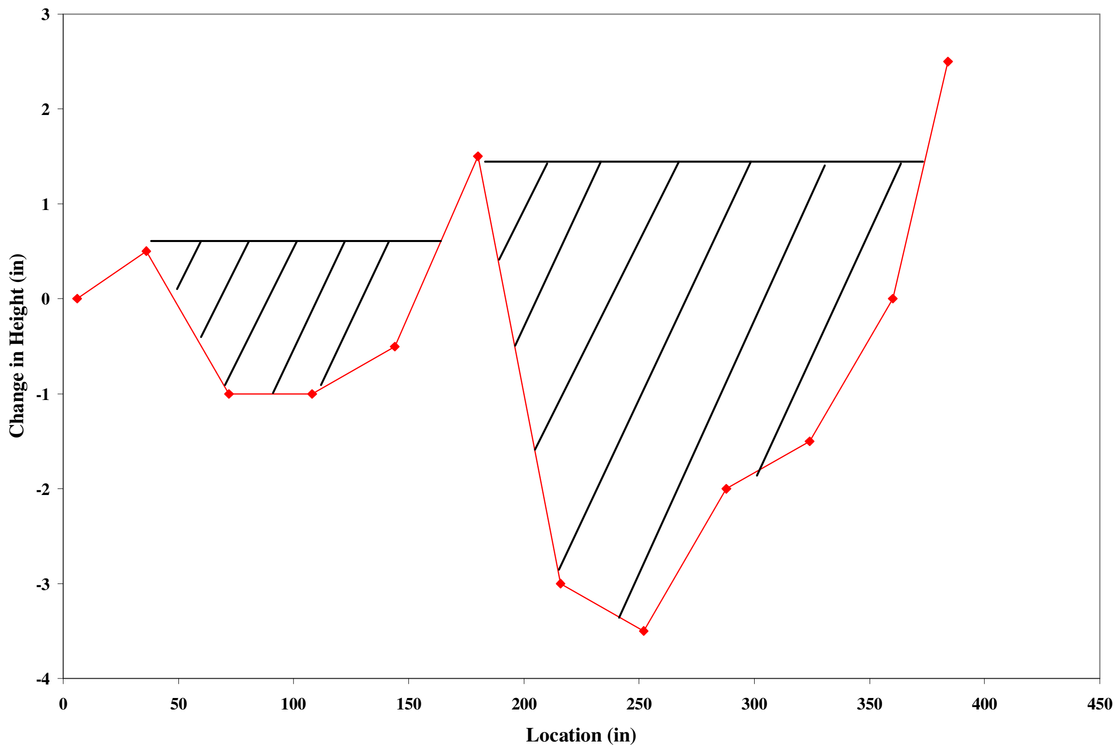

Figure 3.5. Potential water collection areas- module 7.

The system was left installed on the module builder after the initial testing. The harvesting crew continued to use the system, and modules built with the system were marked. On 12 December 2006, the heights of 18 modules built by the same harvesting crew were measured. The modules were at the gin and covered at that time. Half of the modules had been built using the feedback system, but the operator was unknown. All the module builders were the same model. Again, the potential water collection areas were compared for the modules built with the system and without.

3.4. RESULTS AND DISCUSSION

3.4.1. Display Accuracy

The feedback system identified 74.7% (5394 of 7217) of the compression strokes correctly. However, a significant proportion of compression strokes not identified or identified at the wrong location or height were in three modules (table 3.2).

Table 3.2. Accuracy of algorithm in identifying compression strokes by module.

Module #	% Compression Strokes Identified Correctly
1	64.7%
2	64.4%
3	82.6%
4	89.8%
5	56.2%
6	72.7%
7	78.5%
8	85.9%
9	91.6%
10	84.9%
11	90.1%
12	83.3%
Total	**74.7%**

Initially, the tramper outlier threshold was set to 45.6 cm (18 in). The tramper was observed to regularly exceed this threshold between sensor readings during construction of modules one and two. This source of error accounted for 17% of all compression strokes not identified correctly, even though the lower threshold was only used for two modules (figure 3.6). Therefore, the outlier threshold was changed to 79.8 cm (31.4 in) for the remainder of testing, largely eliminating this source of error.

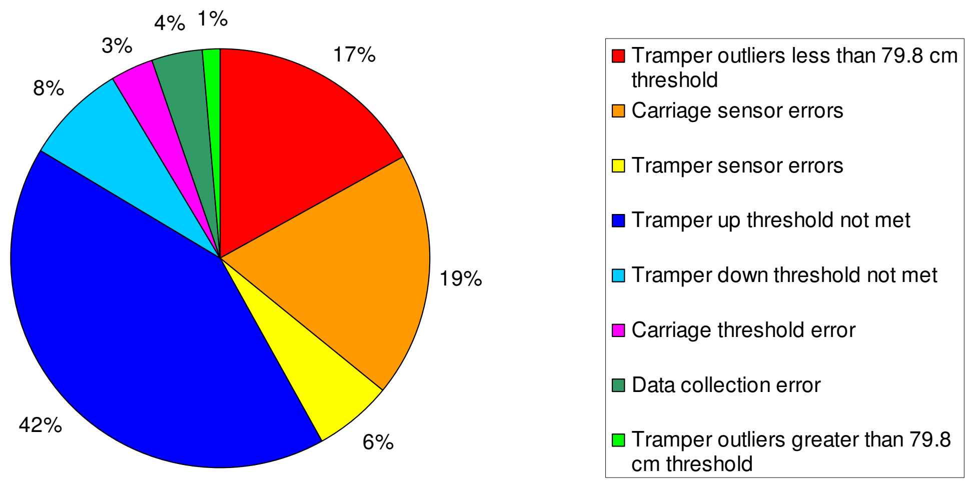

Figure 3.6. Errors in identifying tramping strokes.

Another significant cause of failure to identify compression strokes properly were carriage sensor errors that occurred on module five. One source of carriage sensor error was the use of the automatic tramping system. Actuating a solenoid valve required significant current. The alligator clips connecting the automatic tramping system cable to the tractor battery terminals were corroded and a significant voltage drop occurred across these clips. The voltage could become too low to power the proximity sensors that indexed the carriage. When the solenoid was de-energized, the proximity sensors were powered again. Anytime power was supplied to these proximity sensors, a pulse was generated, indexing the carriage to the front. There were also been problems with proper alignment of the carriage position sensors and the sensing hub, and mechanical damage to the proximity sensor resulted.

Modules six and seven were the only other modules with less than 80% of compression strokes correctly identified. While building these modules, the tramping cylinder hoses were occasionally detected by the tramper sensor. This erroneous height measurement was a significant source of error for these two modules.

These errors due to invalid sensor values and the incorrectly set tramper outlier threshold were all corrected during the course of testing. If these sources of error are excluded, 85.3% of the compression strokes can be correctly identified by the algorithm. This figure is comparable to the compression stroke identification rates for modules 3, 4, and 8-12. The remaining compression strokes were not identified correctly due to the design of the algorithm or the values of the parameters used in the algorithm.

The primary cause of compression strokes not displaying was that the difference between the minimum smoothed tramper value and the maximum smoothed tramper value before the carriage moved was less than the threshold necessary to consider an operator action a tramping stroke.

The actual distance retracted by the tramper was often larger than the threshold; however, the exponential moving average introduced a delay into the smoothed values (figure 3.7). This delay is given by the following formula (Hines, 2006):

$$\tau = \frac{1 - \alpha}{\alpha} \tag{3.2}$$

where

τ = delay (number of observations)

α = smoothing factor (weight of current observation).

The smoothed values, shown in red, lagged the actual sensor values, displayed in blue, by 1.5 observations.

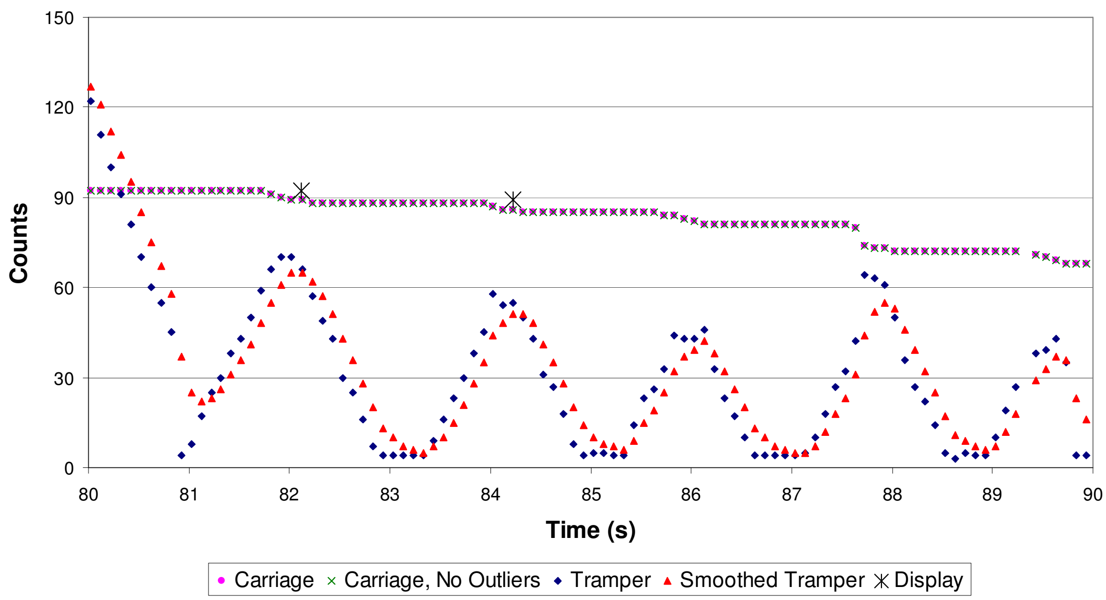

Figure 3.7. Lag in smoothed tramper data resulting in no display.

In this sequence of module builder actions, three tramping strokes were not displayed. The first non-displayed tramping stroke occurred between 84 and 86 s, the second between 86 and 87.7 s, and the third between 87.7 and 89.5 s. In all three cases, the difference between the minimum smoothed tramper height and the maximum smoothed value was larger than the threshold required to qualify as a tramping stroke; however, the delay introduced by the smoothing algorithm resulted in the maximum smoothed height occurring after the carriage moved. When carriage movement began, the difference in the current smoothed tramper value and the minimum value was less than the threshold value, so the program determined that a tramping stroke had not occurred.

A simple solution may be to account for the delay introduced by smoothing the tramper sensor data. Since the delay was not an even number of observations, the software could associate a given smoothed tramper value with the carriage position two readings prior. The smoothing factor could be changed to 0.33, which would have a delay of two observations, or 0.5, which corresponds to a delay of one observation. If a delay of two observations had been used, 68.6% of the compression strokes not properly identified because the upward tramper movement threshold was not met would have been correctly recognized by the algorithm.

Reducing the tramper movement threshold may still be necessary, since some tramping strokes did not display due to the tramper not extending an adequate distance at the start of a tramping stroke. This threshold can easily be changed in the system software and should not adversely affect system performance since no leveling actions were classified as tramping strokes. A tramper movement threshold of 22.9 cm (9 in) may be more appropriate, especially as the module is finished.

3.4.2. Height Prediction

The estimated actual heights of the 12 modules with feedback system data were plotted against the display heights and the regression line is shown in black (figure 3.8). The R^2 value was 0.48, which is lower than desired. However, a great deal of uncertainty existed in determining the estimated actual height. The measuring tape may not have been completely straight across the top or sides of the module and an uneven top surface of the module could result in additional error. The location at which the compression stroke occurs may have differed slightly from where the measurement was made. For these reasons, a height measurement error bound of ±7.62 cm (3 in) was considered reasonable. 67% of the data points fall within these error bounds, which are displayed in blue on the graph.

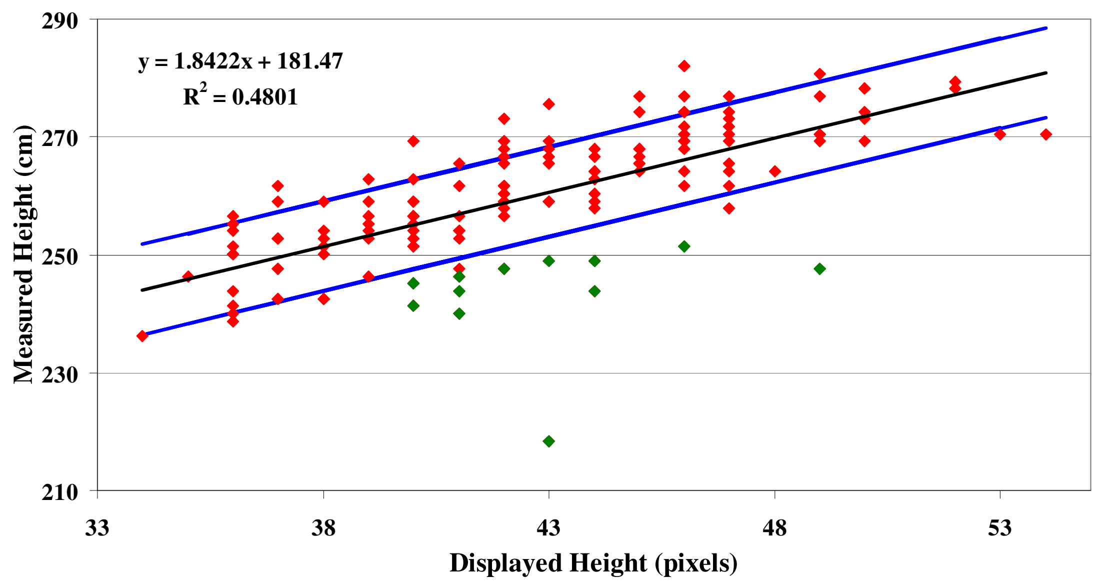

Figure 3.8. Measured and displayed height for all modules.

A more in-depth analysis of the data reveals that all of the data points in module 2 (shown in green in figure 3.8) lie outside of the error bounds and almost all other data points. The actual height was significantly less than what would be predicted using the regression equation. One possible explanation is this module was built at night before wet weather moved into the region. The increased humidity could have caused the module to expand less after the module builder was pulled off, resulting in lower measured heights. The regression line with the module 2 data excluded is y = 1.9005x + 180.51. The R^2 value is now 0.65 and 77% of the data points fall within ±7.62 cm (3 in) of the regression line.

3.4.3. Effect of System on Module Shape

The calculated potential water collection areas for modules built by operator B before and while using the feedback system are shown in table 3.3. The modules built with the feedback system are modules 6-10 in table 3.1. A t-test was performed to determine if the means were significantly different. The resulting *P*-value was 0.052, indicating that using the feedback system immediately improved module quality. Visual observation of the modules supported this result.

Table 3.3. Potential water collection areas (cm^2) from initial testing.

Module	Before System	With System
A	6449	2632
B	11190	4831
C	1931	1595
D	6317	1391
E	3484	2789
Mean	**5874**	**2648**

Table 3.4 shows a comparison of the potential water collection areas of the modules measured on 12 December 2006. The means of the potential water collection areas are not significantly different (*P*-value = 0.252). Generally, all the modules observed on this date were well constructed. The feedback system may have served as a

useful training tool for the operators, enabling them to build well-constructed modules without the system.

Table 3.4. Potential water collection areas (cm^2) of modules measured on 12 December 2006.

Module	Without System	With System
1	93	730
2	697	5574
3	0	3908
4	139	4413
5	1763	4355
6	366	1589
7	2926	1066
8	5383	975
9	502	575
Mean	**1319**	**2575**

3.4.4. Acceptability of System

The module builder operators both stated that the feedback system definitely helped them shape the module. They used the display to direct the boll buggy to unload cotton in regions that had a lower height on the display and found that the feedback system was most useful when finishing a module. Both operators agreed that the shape of the module was accurately represented by the feedback system display. When asked how frequently they used the display, both operators replied, “all the time”, which confirmed observations made during testing. The module builder operators found the feedback system particularly useful in low visibility situations, such as at night and at the far end of the module builder. The feedback system was simple to use, as both operators were successfully trained on the first module each built with the system.

The supervisor's comments echoed the response of the operators. He believed that the feedback system would definitely help his crew. He also thought the display was an accurate representation of the module shape. The supervisor stated that the system lets you know where to tramp more. One of the module builder operators made the same comment, but research and observations have indicated that tramping more in a particular location has little effect (Hardin IV and Searcy, 2008). Cotton needs to be moved to regions of the module with a lower height. Module builder operators need to be aware of this in order to build high quality modules.

3.5. CONCLUSIONS

The operator feedback system accurately displayed the module shape that resulted from the operator's actions. The system correctly identified 74.7% tramping strokes. With properly functioning sensors and an optimal tramper sensor outlier threshold, over 85% of tramping strokes could be identified. Modifying the algorithm to account for the delay introduced by smoothing would increase the accuracy to 92.5%. The minimum tramper height calculated during a tramping stroke was an accurate predictor of module height. With the exception of one module, 77% of predicted heights were within 7.62 cm of the actual module heights.

The feedback system resulted in an immediate improvement in module shape when first used by an operator, with the potential water collection area of the modules measured reduced 55%. However, a training effect was observed, since later modules were generally constructed with desirable shapes regardless of system use.

The system was easily used and understood by the operators. The system was used to guide boll buggy operators to unload in areas with less cotton. Module builder operators also found the system useful in low-visibility situations– at the far end of the builder and at night. The feedback system is a useful and inexpensive tool in building modules with shapes that will not collect water.

4. COMPRESSED BIOMASS PACKAGE MEASUREMENT SYSTEM

4.1. INTRODUCTION

No automated system currently exists for quantifying the size and shape of large compressed packages of biological materials, such as cotton modules. These packages are commonly stored outdoors for an extended time; consequently, preventing the collection of water on the surface may be necessary to maintain the quality of the stored product. These packages should have a crowned top surface with no depressions where water can collect. A measurement system needs to be developed so that techniques and equipment for constructing packages with improved shapes can be quantitatively evaluated. One application of such a measurement system is in evaluating cotton module builder improvements which assist the operator in moving a greater mass of cotton to the center of the module.

4.1.1. Objectives

Related research has developed systems to produce large biomass packages with crowned shapes that prevent the collection of water on the top surface. The goal of this project was to develop equipment for quantifying the shape of these packages to evaluate these improvements. Specific objectives of this research were:

- Design equipment to record height at multiple points on the top surface of biomass packages to quantify the shape of the package.

- Develop algorithms to process height data into useful variables by identifying and characterizing the depressions in the top surface of the package.
- Evaluate the accuracy of the system in measuring the surface height of large biomass packages.

4.2. LITERATURE REVIEW

The lack of a suitable measurement system has been an impediment to research on improved cotton handling systems. Researchers have generally agreed that cotton modules need to be built with a crowned surface (Willcutt et al., 1992). No objective technique has existed for comparing module shapes or correlating module shape with quality losses.

For instance, Brashears et al. (1993) theorized that depressions on a module surface caused moisture damage with a spray-on module cover. Higher moisture content was observed in areas corresponding to lower regions on the surface, but no in-depth analysis could be done. Simpson and Searcy (2005) identified poorly shaped modules as a significant cause of decreased lint value; however, module shapes were identified subjectively.

A manual technique has been utilized to quantify the shape of cotton modules for evaluating an operator feedback system for the module builder (Hardin IV and Searcy, 2006). This technique involved placing a measuring tape over the top of the module and recording the distance from the ground on one side of the module to the ground on the other side. This method was used because the measurement provided an estimate of the average height at a given location along the length of the module and removed the subjective determination of where the top of the module was when making a measurement on only one side. However, this method was time-consuming and labor intensive, requiring approximately 10 minutes per module for two people to make 12 measurements.

The measurement error of this method was estimated to be ±7.62 cm (3 in.) due to errors in aligning the measuring tape on each side of the module and irregular module surfaces. Most importantly, this technique only provided an estimate of the height of the sides of the module. No quantitative information about depressions in the top surface could be obtained. While this estimate was useful in quantifying the performance of the feedback system, evaluation of other module builder improvements required more information about the top surface profile. For instance, this manual technique would not be adequate for evaluating the performance of a device that moved cotton from the sides of the module to the center. A system to measure the height of multiple points on the surface of large biomass packages would be a useful tool for researchers.

4.3. MATERIALS AND METHODS

4.3.1. Design Specifications

The measurement system was mounted on a truck driven alongside the package, with all components having a mass less than 23 kg (50 lb). These requirements ensured that the system was portable and could be set up and operated by one person. The system should be capable of measuring biomass packages from 1.52 m (5 ft) to 3.05 m

(10 ft) in height. A maximum variation in height of 61 cm (2 ft) across the width of the package could be measured by the system. The full range of variation in height measurements applied to the entire length of the package. The system should be capable of measuring a package 1.83 m (6 ft) wide. There was no limit on potential package length, since the system traveled the length of the package.

The measurement system should produce a surface of package heights with a maximum distance of 15.24 cm (6 in.) between adjacent points on the surface. A minimum height resolution of 3.18 mm (0.125 in.) was desired to maximize the overall accuracy of the height measurement system. The sensors used for these measurements should draw less than 100 mA to maximize battery life.

4.3.2. System Design

This system was mounted on a truck, which was driven alongside packages to record heights. As the truck drove along the package, a spring-loaded parallel linkage kept the system properly positioned against the package (figure 4.1). Two star-shaped distance measuring wheels contacted the package and rotated as the system moved along the length of the package (rear distance measuring wheel shown in figure 4.2). These wheels have a maximum diameter of 25.4 cm (10 in) and were coupled to rotary encoders (Automation Direct model TRD-N60-RZWD) to determine the distance traveled along the length of the package. These quadrature encoders output 60 pulses per revolution at a maximum speed of 5000 rpm.

Figure 4.1. Parallel linkages and position sensing apparatus.

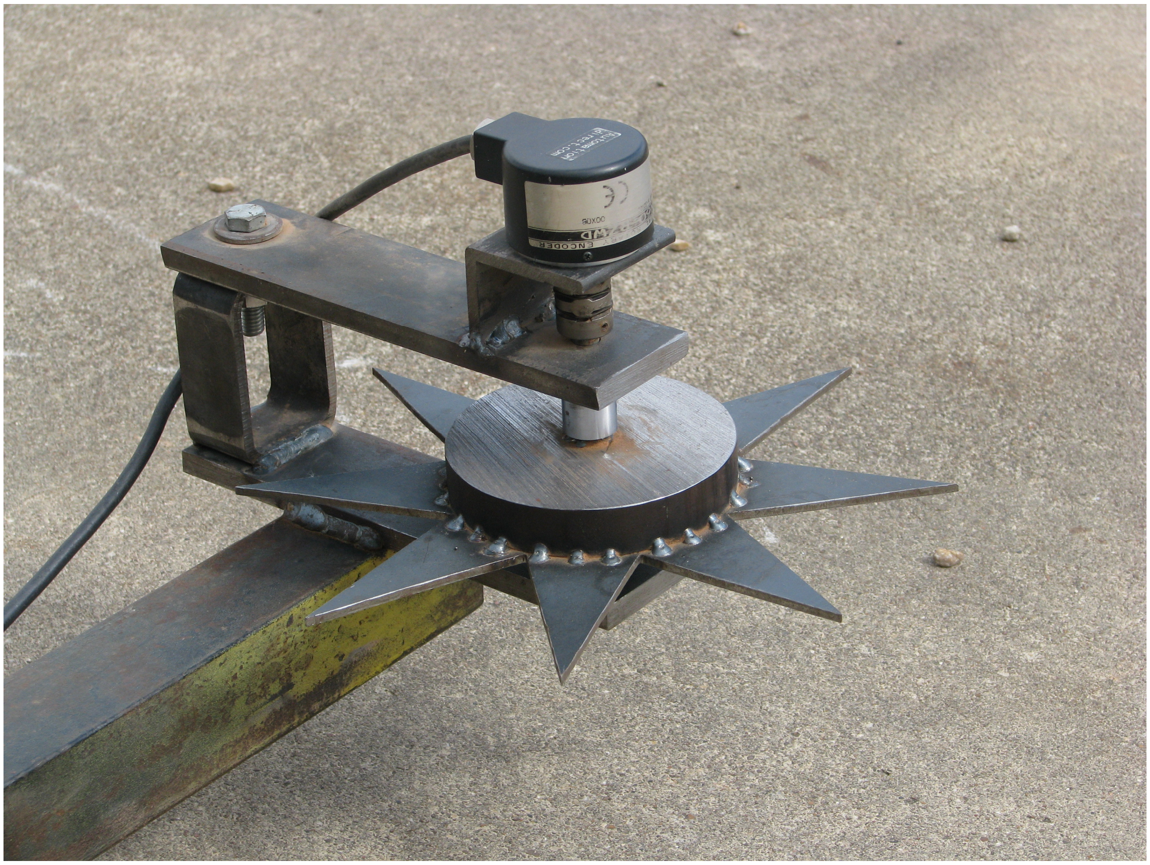

Figure 4.2. Distance measuring wheel assembly.

The surface height was measured by 13 fingers mounted 15.24 cm (6 in.) apart on a horizontal arm (figure 4.3). These fingers were constructed from ultra-high molecular weight polyethylene (UHMW), 60.96 cm (24 in.) long by 1.27 cm (0.5 in.) diameter. The fingers mounted to ETI Systems EUP1100 rotary potentiometers and were free to rotate as they moved along the surface. These 10k Ω potentiometers have a maximum deviation from linearity of 1%, or 100 Ω.

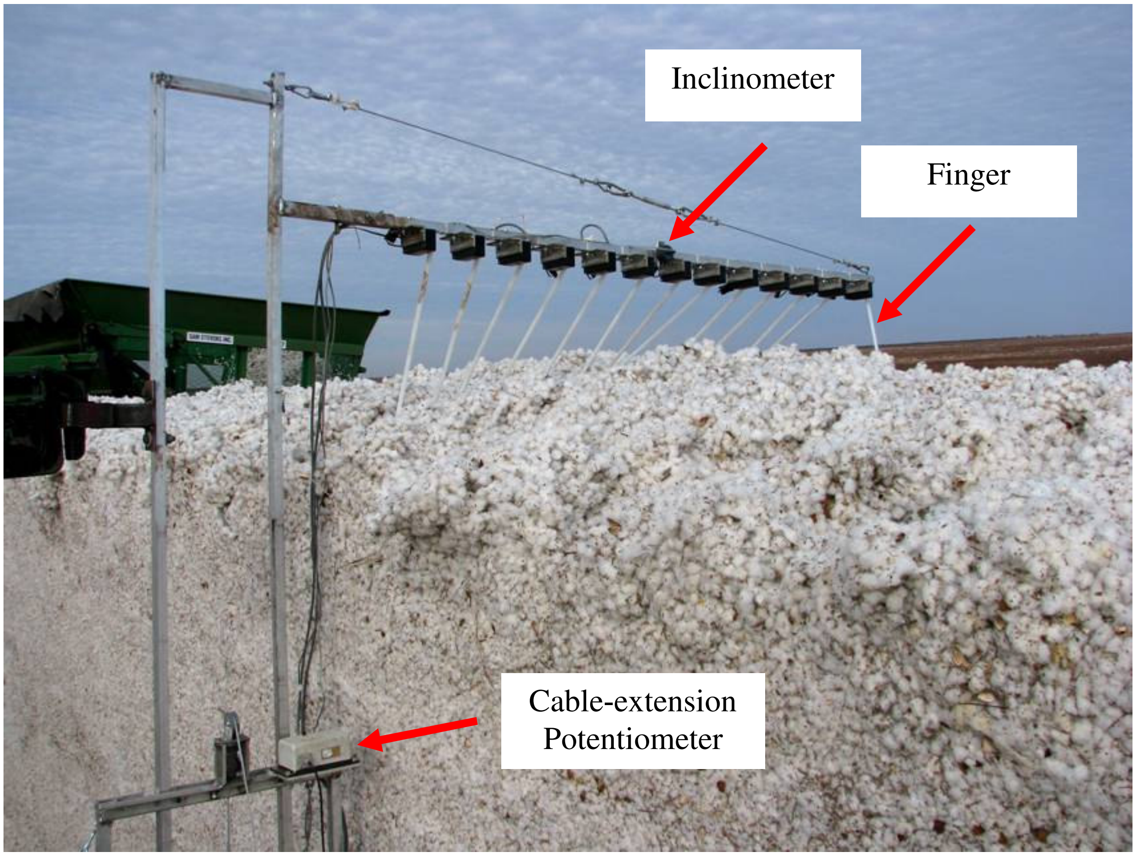

Figure 4.3. Height measurement sensors.

The movement of the fingers when in contact with a biomass storage package is detailed in figure 4.4. When a depression in the surface is encountered the fingers rotate forward, resulting in a smaller angle, θ, from the vertical. Higher regions result in the fingers rotating upwards.

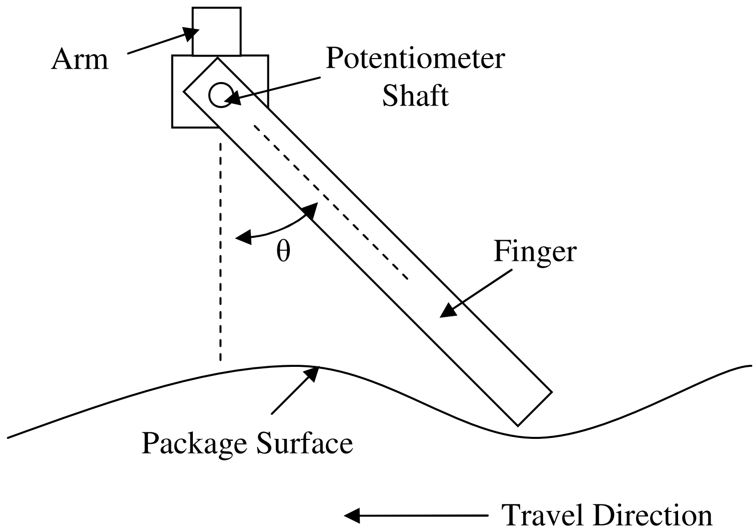

Figure 4.4. Cutaway view of finger contact with package surface.

As the measurement system traversed the length of the biomass package, rough terrain could cause the arm to experience significant deflection from the horizontal position (figure 4.5). A Sperry AccuStar inclinometer measured the angle, φ, from the horizontal to the arm where the fingers were mounted. In figure 4.5, the measured height would be adjusted downward to account for the displacement of the sensing arm. This inclinometer has a linearity of 0.1° over the range of angles observed and a repeatability of 0.05° with a measurement threshold of 0.001°. Although this motion of the arm also imparts a lateral displacement to the fingers, this effect should be small since the angular motion of the arm, φ, is limited to several degrees. Additionally, the fingers still remain parallel with the same lateral spacing.

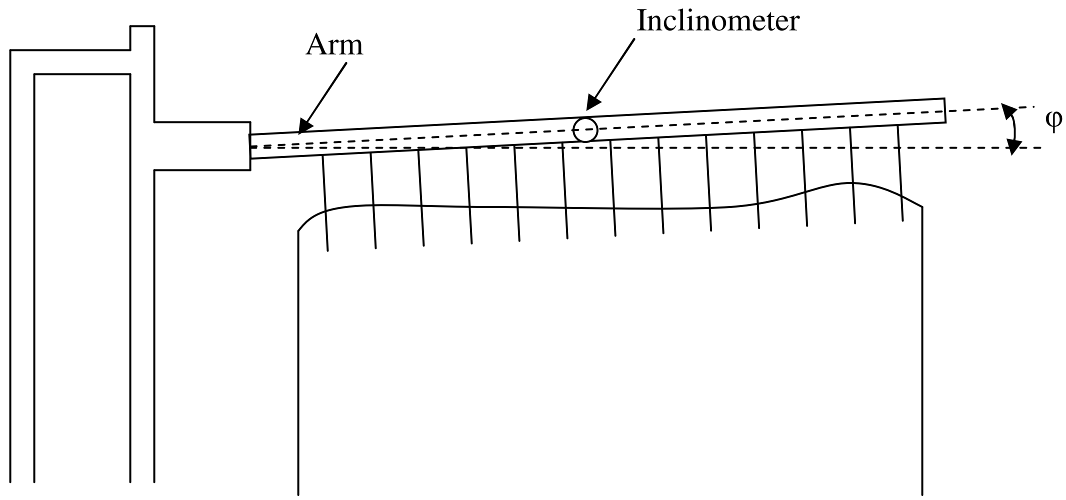

Figure 4.5. Angular deviation of arm measured by inclinometer.

The arm and fingers were mounted to a mast that was raised or lowered with a winch so the fingers maintained contact with the surface (figure 4.6). An adjustable height mast needed to be used to accurately measure the full range of package heights that would be encountered. If the arm was mounted at a fixed height, the fingers would need to be at least 1.52 m (5 ft) long to measure a range of heights from 1.52 m (5 ft) to 3.5 m (10 ft). With this design, the resolution of height measurements on taller packages would decrease significantly, since a given angle of rotation corresponds to a much greater change in height when the finger is closer to a horizontal position than a vertical one. The desired height measurement resolution could be achieved and a larger range of package sizes could be measured using the adjustable height mast.

Figure 4.6. Adjustable height mast.

Lengths of wire rope with turnbuckles were used to provide additional support to the arm and mast. The height of this mast, relative to the base of the measurement system, was determined with a Celesco PT101 cable-extension potentiometer. This potentiometer has a range of 152.4 cm (60 in.) and an accuracy of 1.5 mm (0.06 in.). The rotary potentiometer, inclinometer, and cable-extension potentiometer values were used to calculate the height at points where the fingers contacted the package.

Regulated 5 V power was supplied to all sensors and D flip-flops were used to convert the quadrature encoder outputs to clockwise and counterclockwise pulse trains. The potentiometers, inclinometer, and flip-flop outputs were connected to a Campbell Scientific 21X datalogger. The datalogger voltage measurement accuracy was 2.5 mV from 0-40°C and 5 mV at temperatures outside this range. The datalogger was capable of counting pulses up to 2550 Hz, significantly faster than the actual pulse rate produced by the measurement system encoders. The datalogger was configured to record data if any encoder pulses were detected in the minimum time interval of 0.0125 s.

4.3.3. Data Processing

This sensor data was initially processed to convert the recorded values to the package height at a given position along the package's length and width. The string potentiometer and inclinometer were calibrated in the lab. Zero position values for the rotary potentiometers, corresponding to the voltage output with the fingers in a vertical position, were determined using two methods. Actual data in the field was used, since the voltage output of each rotary potentiometer varied for the same finger position and packages could potentially be built on a slope.

For data on the first 15 modules measured, the rotary potentiometer values were averaged from the initial reading until five records prior to where the fingers contacted the module. A more accurate method of determining these zero position values was desired. For the remaining modules, the rear distance measuring wheel was manually rotated in reverse while the system was stationary. The potentiometer readings during this action were averaged to provide zero position values.

The algorithm identified the point where the fingers first contacted the package as the data record where at least eight of the rotary potentiometers had a decrease in output voltage of at least 10 mV. When the measuring system reached the end of the package, the fingers rotated forwards past vertical and the rotary potentiometer output values exceeded the zero position values. The final contact point was determined to be when all the fingers had exceeded the zero position values. If a rotary potentiometer exceeded its zero position value in the five observations previous to the final contact point, the observations for this particular potentiometer were ignored until the potentiometer output was less than the zero position value.

Two distance measuring sensors had to be used to ensure that the distance traveled was recorded at all times while the fingers were in contact with the package. Initially, the front distance measuring wheel contacted the package and the front distance measuring sensor was used for distance measurements. Both distance measuring wheels should be in contact with the package for the majority of the package's length. However, if the angular deviation of the measuring system from a track parallel to the package was large enough, one measuring wheel would not contact the package. During the period both sensors should contact the package, skipped pulses were identified and corrected. After the front measuring wheel had moved past the end of the package, the rear distance measuring sensor was used for distance measurements.

The total distance traveled while at least one encoder was in contact with the module was 11 m (433 in.)– the length of the module plus the distance between the two encoders. The circumference of the measuring wheel was 79.8 cm (31.4 in.); therefore, traveling this distance would theoretically result in one rotation of the measuring wheels. The total number of encoder pulses counted (the combination of the two encoders) would be 827 for the entire 11 m travel length. However, the measuring wheels actually rotated more than one complete rotation in 79.8 cm of travel. This behavior was likely due to the measuring wheels having a smaller effective diameter than their maximum diameter due to small differences in the density of seed cotton or void spaces created by the measuring wheels.

The additional rotation observed during measurement was small and consistent between observations, so this effect was accounted for while processing data. The total number of encoder pulses, after correction for skipped pulses, was used to scale the position data from 0-11 m. For example, if the total number of encoder pulses recorded was 935, each pulse would correspond to 1.18 cm of movement along the length of the module. The total number of encoder pulses recorded was also used to identify invalid measurements.

For each rotary potentiometer measurement, the height was calculated by determining the height of the mast from the string potentiometer reading, adjusting for the deviation of the arm from the horizontal using the inclinometer, and determining the vertical distance from the arm to the end of each finger, as shown in the following equation:

$$z_{surface} = z_{mast} - 58.42 * \cos\theta - (39.37 + 15.24 * j) * \tan\phi \tag{4.1}$$

where

$z_{surface}$ = surface height (cm)

z_{mast} = mast height (cm)

θ = angle of finger with vertical

j = the position of the rotary potentiometer used in the calculation (from 0-12)

φ = angle of arm with horizontal.

The constant 58.42 represents the length in cm of the finger from the potentiometer shaft to the end in contact with the surface. The other two constants give the distance in cm along the arm from where the mast attached to a given rotary potentiometer.

The width coordinate was given by the finger's position along the length of the arm. The location along the length of the package was determined by calculating the distance from the start of the package from the encoders and subtracting the horizontal distance from arm to the end of the finger. The height measurements will be irregularly spaced in the direction of travel (along the length of the package) due to the adjustment for the movement of the finger:

$$y_{surface} = y_{encoder} - 58.42 * \sin\theta \tag{4.2}$$

where

$y_{surface}$ = location of height measurement along length of package (cm)

y_{mast} = location of encoders along length relative to starting position (cm).

Because the front encoder contacted the package before the fingers did, the minimum value of $y_{surface}$ was greater than zero. After the height of the surface and the location of all measurements were calculated, the $y_{surface}$ values (position along the length of the package) were adjusted by subtracting the minimum value, resulting in a starting position along the length of zero. This operation was only done to aid in interpretation of results and does not affect any further analysis.

Once the location of height measurements along the width and length of the package were determined, further processing was done to develop useful parameters for a statistical analysis. A primary objective in developing this system was to characterize the surface topology of large compressed biomass packages. These packages are likely to be stored outdoors and should have a top surface with no depressions where water could collect. As a result, the surface height data was analyzed to identify depressions where water could collect.

MATLAB (2007) programs were developed to provide information about the surface depressions. The data collected contained module heights on a grid with irregular spacing in the direction of the module length (due to the rotation of the measuring fingers). For further processing, this data had to be converted to a regular grid spacing. The *GRIDDATA* function in MATLAB was used to interpolate the data to a regular 15.24 cm (6 in.) grid spacing. Using the interpolated heights at grid points, local minima and maxima were identified by comparing each point to its four cardinal neighbors.

Contours were taken, using the *CONTOURC* function, from the global minimum to the global maximum, with an increase in height of 0.01 mm between each step. This step size was selected because larger step sizes did not significantly alter the calculated depression volume and required excessive computational time. Contours corresponding to a depression were identified by using the following rules:

1. The contour must form a closed polygon; otherwise, water on this region of the module surface will drain off the module.
2. A local minimum must be located within the contour. A contour containing no local minimum corresponds to a peak on the module surface.
3. No local maximum can be contained within the contour, except for the following two conditions:
    a. The maximum is located in another contour polygon that is completely enclosed in the original polygon. The local minimum is located in the region between the polygons. This scenario describes an island within the depression.
    b. The height of the maximum is less than the contour height- if the depression was filled with water, the maximum would be submerged.

For contours that correspond to a depression, the area of the contour polygon was calculated. In the case of concentric polygons (rule 3a above), the difference in the area of the two contour polygons was calculated. Volumes were calculated by multiplying the average of successive contour areas by the height step size, 0.01 mm. For each observation, the total depression volume, number of depressions, average depression volume, volume of the largest depression, average depression depth, and average depression surface area were calculated.

Average heights along the length and across the width of the module were also calculated from the interpolated module height data, generating average profiles of the length (figure 4.7) and width (figure 4.8). Depressions were identified by examining the regions between two local maxima. For each profile, the areas of depressions were calculated. The depressions indicated in this module are actually quite small, as the images have been magnified to illustrate these depressions.

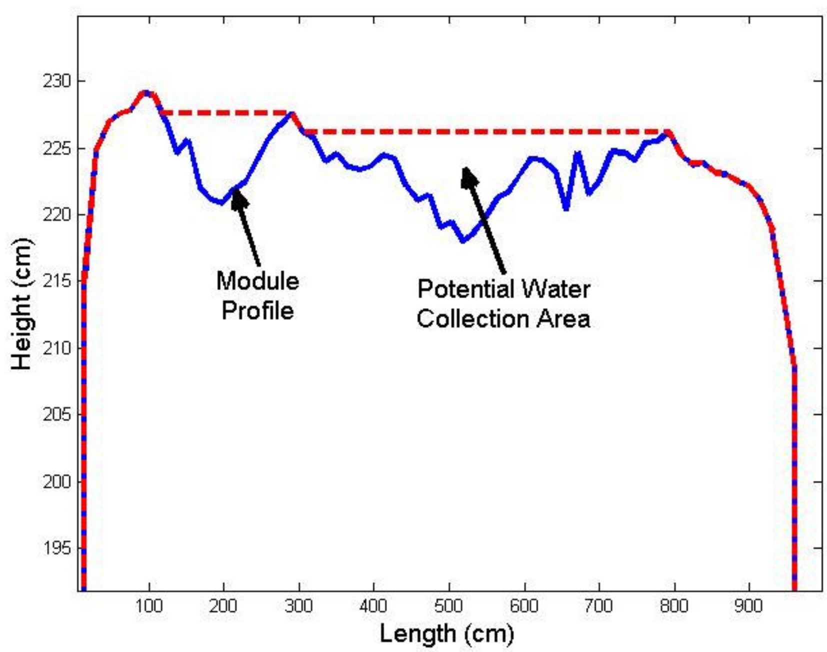

Figure 4.7. Average height along length.

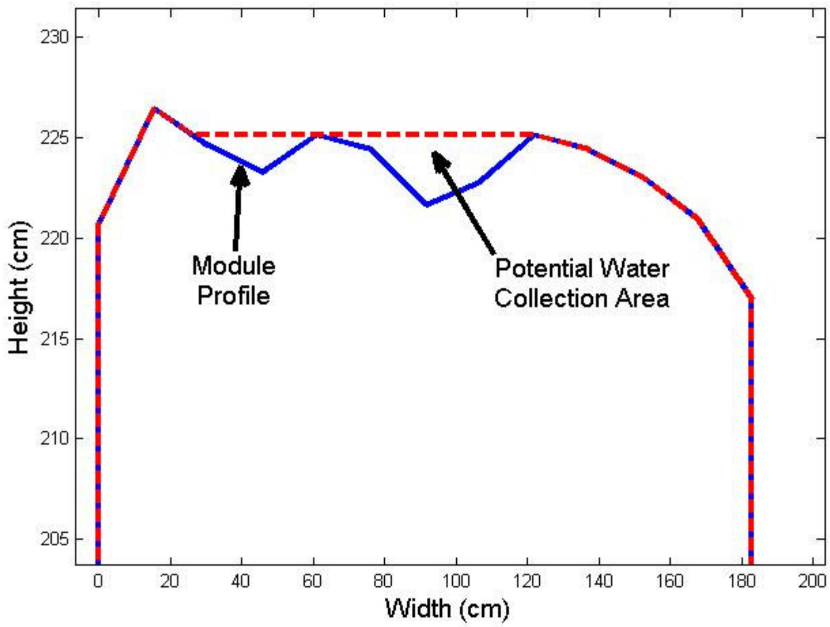

Figure 4.8. Average height across width.

4.4. RESULTS AND DISCUSSION

A total of 44 measurements on 29 cotton modules were conducted with the measurement system. Multiple measurements were performed on some modules to establish the repeatability of the system. Two measurements were noted to be invalid– the end of one module was broken while moving the module builder and at least one measuring wheel was not in contact with another module at all times during the measurement. One additional measurement had a total number of encoder counts less than the measurement where the encoders were not in contact with the module. A loss of measuring wheel contact was assumed to have occurred, and this observation was not used for further analysis. The remaining 41 observations were made on 28 modules.

Ten modules had two measurements made, while three modules had three measurements conducted.

For the 41 valid observations, the mean total encoder count was 935, 13% larger than the theoretical count of 827. The effective diameter of the measuring wheel was 22.5 cm (8.8 in.). Furthermore, the total count for all valid observations varied from 887 to 999, with a standard deviation of 22.8 counts.

Figure 4.9 shows the module height surfaces and depression areas (displayed in black) created in MATLAB for repeated measurements of one module. The measured surfaces are quite similar, showing the same pattern of high and low regions.

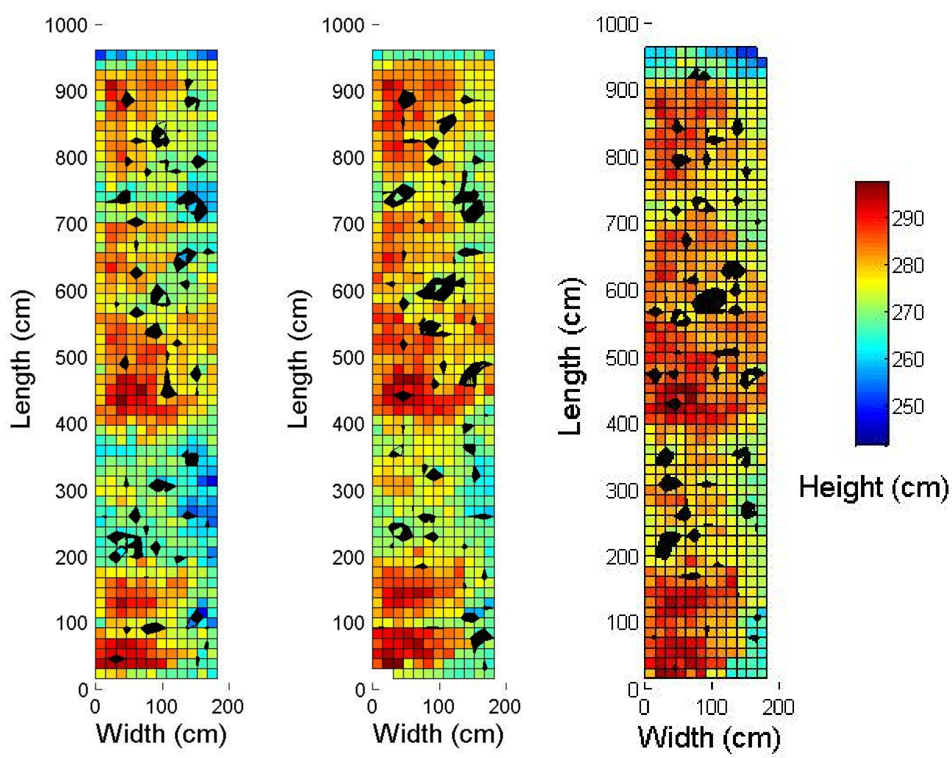

Figure 4.9. Module height surfaces and depressions for repeated measurements on module 18.

A numerical analysis of this height data from repeated measurements on modules was performed to confirm the visual observations (table 4.1). For each grid point, the absolute differences in the heights between two observations were calculated. These absolute differences were averaged over the entire module to produce a mean height difference between the two observations. Because the accuracy of measuring the absolute height was not as critical as measuring the relative height of points on the module surface, each observation's array of heights was also normalized by subtracting the mean height for that observation. These normalized heights were compared in the same manner as the actual heights. Likewise, the height surfaces were also compared to a flat surface at the mean module height.

Table 4.1. Mean height differences between grid points. Module numbers with an asterisk had three measurements, so the mean height difference is an average of the three pairwise comparisons.

Module	**Mean Height Difference (cm)**	**Mean Normalized Height Difference (cm)**	**Mean Difference with Flat Surface (cm)**
1	10.0	7.8	14.4
3	9.1	4.9	19.6
5	8.3	7.0	9.0
16*	4.5	4.5	10.8
17*	5.6	5.6	8.9
18*	4.0	3.9	6.0
21	3.2	2.8	7.8
23	3.6	3.4	10.1
28	3.1	3.0	11.3
29	6.2	5.4	10.6
Mean	**5.4**	**4.8**	**10.6**

The module height measurements were highly repeatable. The primary source of variation was the surface topology as indicated by the mean normalized height difference of 4.8 cm. This value provides an estimate of the measurement error when comparing the relative height of points on a surface. Since the mean height difference was only slightly larger, differences in module height did not contribute significantly to the measurement error. The mean height difference and mean normalized height difference are significantly less than the mean difference with a flat surface. This result indicated that the measurement system could distinguish the surface topology of a package from a flat surface, which is necessary to perform a useful analysis of package shapes.

The first three modules in the table have a greater measurement error than the remaining modules. On these modules, the repeated measurement was done on opposite sides of the module. This difference in repeated measurements was still less than the height difference with other modules. Taking repeated measurements on opposite sides also tended to increase the mean height difference (average of 9.1 cm for modules 1, 3, and 5) more than the mean normalized height difference (average of 6.6 cm for the same modules). This result indicated that measuring opposite sides of the module reproduced the relative heights of surface points nearly as well as measuring on the same side; however, there is additional error in the height relative to the ground. Improved operator performance may have also contributed to the reduced height differences between repeated measurements.

While the heights calculated for repeated observations on the same module have little variation, the total volume of the depressions calculated for repeated observations showed more variation. This result was likely due to the sensitivity of the depression calculation to individual height measurements. If only one height measurement corresponding to the border of a depression is lower, the depression volume will be much less or the depression may not exist. This sensitivity of depression sizes is illustrated in figure 4.8. Table 4.2 displays information about the depressions in module 16 (figure 4.10) and module 18 (figure 4.9).

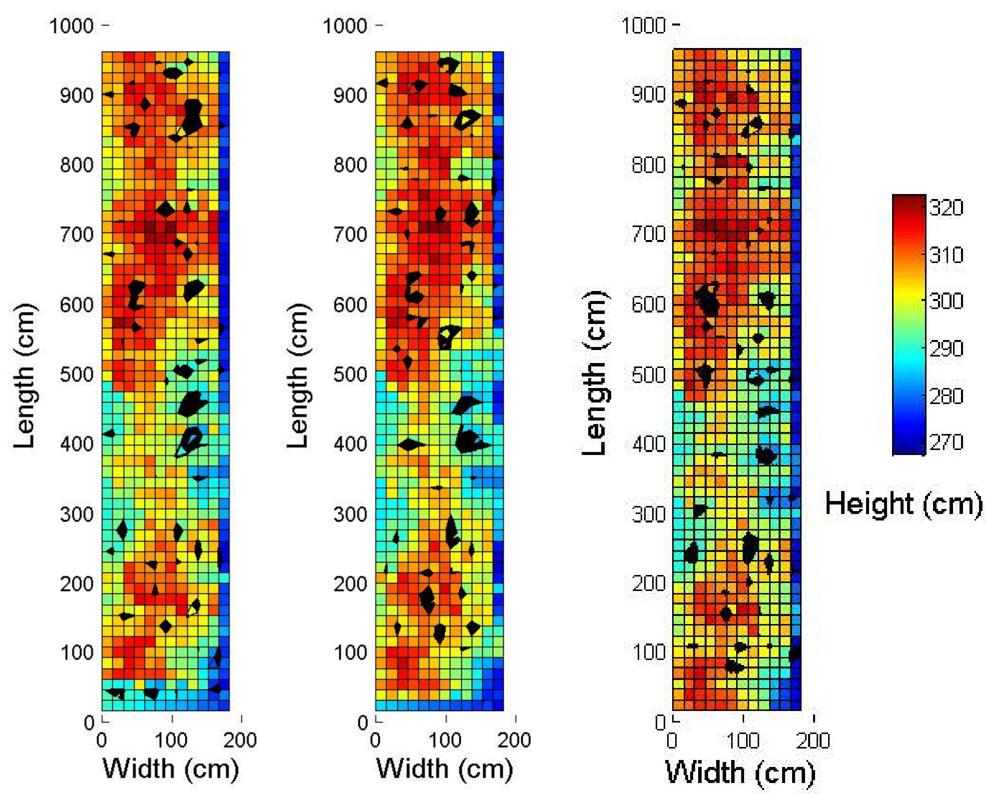

Figure 4.10. Module height surfaces and depressions for repeated measurements on module 16.

Table 4.2. Depressions for observations of modules 16 and 18.

Module	Observation	Total Volume (L)	Number of Depressions	Largest Depression Volume (L)
16	a	16.3	55	3.6
	b	14.5	56	2.7
	c	9.3	53	1.9
18	a	10.9	53	1.8
	b	13.5	55	2.3
	c	12.4	53	2.6

The large variation in the volume of depressions between observations of module 16 is primarily due to the size of the several large depressions, shown on the right side of the module (located along the length at approximately 400, 450, and 850 cm). These depressions are much larger in the first two observations, even though the module height surfaces are similar. Module 18 did not exhibit this variation in the size of a large depression and consequently, the total depression volumes are similar.

Table 4.2 illustrates that the largest depression alone accounts for a significant percentage of the total depression volume. In fact, many of the depressions observed were quite small, as shown in the cumulative distribution function of depression sizes in figure 4.11. The volume is less than 0.1 L for 65% of the depressions and 85% have a volume less than 0.3 L.

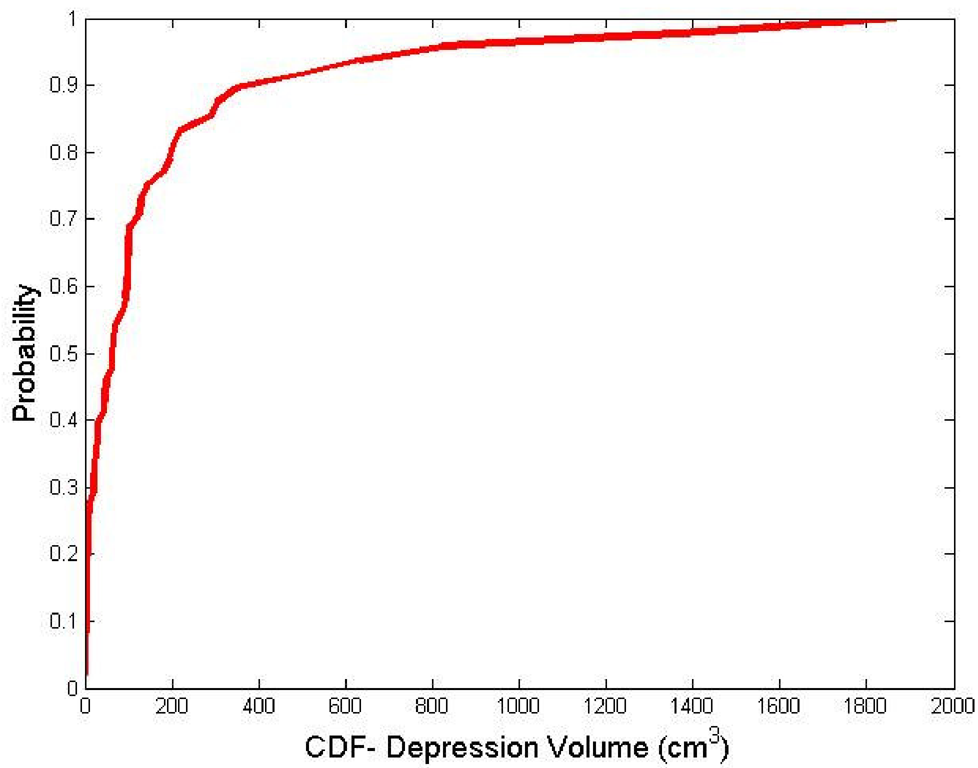

Figure 4.11. Cumulative distribution function for depression volume in module 1, observation 2.

Because the mean height difference between repeated measurements, normalized for the mean height, was 4.8 cm, the validity of small depressions identified by the system was questionable. These smaller depressions are not likely to be practically significant. Larger depressions were consistently identified across repeated measurements, although their dimensions could vary.

4.5. CONCLUSIONS

The measurement system recorded the height at multiple points on the surface of large biomass packages. Height measurements on cotton modules were highly repeatable, with a mean normalized height difference between repeated measurements of 4.8 cm and a mean height difference between repeated measurements of 5.4 cm. The effective diameter of the measuring wheel was 88.5% of the actual diameter when used with cotton modules. Algorithms were developed to identify and characterize depressions in the module surface. Larger depressions were consistently identified in repeated measurements, although their volumes occasionally varied significantly due to the sensitivity of the depression volume to individual height measurements. This system should be useful in evaluating the capability of compressed biomass packages to resist water collection on the surface.

5. POWERED TRAMPER

5.1. INTRODUCTION

Preserving the quality of seed cotton stored in modules is an important goal of cotton producers and ginners. Building properly shaped modules is a key component of cotton quality preservation during storage. Modules should be constructed with a crowned top surface and no depressions where water could collect. Module covers are often weathered or damaged and will allow water collected in depressions to leak through to the cotton.

The cotton unloaded from a harvester or boll buggy is not generally distributed evenly across the width of the module, resulting in depressions in the top surface. No mechanical system exists to distribute cotton from the sides to the center of the module. The only method of accomplishing this task currently is to manually move the cotton. Using manual labor to move the cotton is difficult, inefficient, and potentially unsafe. Consequently, a system to move cotton from the sides to the center of the module builder could provide significant improvements in cotton quality.

5.1.1. Objectives

This research was conducted as part of a larger study to develop improved storage and handling techniques to preserve seed cotton quality. The primary goal of this project was to design and test a modification to the module builder that will provide the capability to move cotton across the width of the module, producing a module that is higher in the center than at the sides. The objectives of this research were:

- Design a mechanical system to move cotton from the sides to the center of the module builder.
- Evaluate the shapes of modules built using the system.

5.2. LITERATURE REVIEW

Modules with undesirable shapes were found to lose $200 in lint value compared to properly shaped modules if significant rainfall occurred (Simpson and Searcy, 2005). This loss occurred with both good and poor quality covers. Producers need to build modules with shapes that will not collect water to preserve cotton quality. However, many cotton modules have less than desirable shapes, resulting in significant economic costs for the cotton industry. Simpson and Searcy (2004) determined that one-half of the modules at Texas gins had poor shapes that would collect water.

To produce a module with a convex top surface, more cotton must be placed in the center of the module (Hardin IV and Searcy, 2008). Cotton needs to be moved both along the length and across the width of the module to result in the most desirable shape. Hardin IV and Searcy (2007) developed a feedback system that accurately displayed the module shape to the operator. This system assisted the operator in moving cotton to the appropriate location along the length of the module builder.

However, no technique exists to move cotton from the sides to the center of the module builder. Some module builder manufacturers have designed arched trampers to attempt to impart a crown across the width of the module. The results of the study on the physical properties of seed cotton by Hardin IV and Searcy (2008) and observations of modules built with this tramper shape indicate that the design is ineffective. The shape of a cotton module depends on the relative distribution of mass in the module. Areas containing a greater mass of cotton will have a greater height. A larger mass of cotton needs to be in the center of the module, relative to the sides, to produce a crowned surface.

Preliminary work in the laboratory using a compression testing apparatus and a 1/8-scale module builder indicated the suitability of using an auger to both move cotton along the auger axis and compress cotton (Schulte, 2007). Other methods of moving cotton, such as using a belt with cleats or a finger wheel, had proved ineffective or resulted in cotton plugging in the moving components of the device. An auger inside a housing compressed cotton to a similar width and depth as a conventionally shaped tramper with the same dimensions as the housing. 2.2 kg (4.8 lb) of cotton were moved per tramping stroke when the auger motor received three times the flow of the tramping cylinder and was stopped when the pressure drop across the motor reached 5.5 MPa (800 psi).

This early design was not suitable for implementation on a module builder for several reasons. Flow was diverted from the tramping cylinder to the auger motor using a flow control valve. Delivering adequate flow to the motor would require diverting too much flow, resulting in unacceptably slow operating times. Auger operation was stopped using a pressure relief valve, resulting in a significant amount of wasted energy.

The preliminary design only moved cotton in one direction, while a full-scale prototype would need to move cotton from both sides of the module builder without plugging.

5.3. MATERIALS AND METHODS

5.3.1. Design Specifications

The powered tramper should be easily retrofit to existing module builders and operate automatically. The operating speed and maximum tramping force of the module builder need to remain unchanged so quality modules can be constructed quickly. The device should allow free movement of cotton at all times by minimizing areas where cotton could collect or including mechanisms to clear cotton from these areas. Clearing plugged cotton from the system would be time-consuming and potentially dangerous.

5.3.2. Mechanical Design

The powered tramper replaced the conventional tramper. The auger housing was bolted to the support columns and supplied most of the compressive force. The bottom members of the housing were 1.6 mm (0.0625 in.) lower than the bottom of the pipe where the auger flighting was welded (figure 5.1). Only the flighting was lower than the housing.

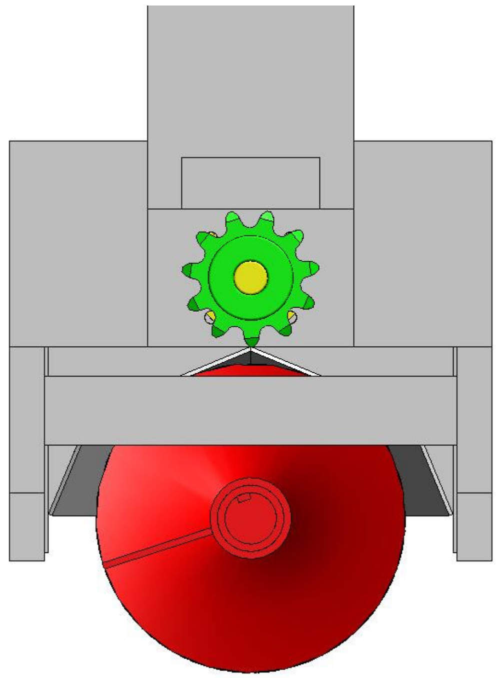

Figure 5.1. Side view of powered tramper (bearing and sprocket removed for visibility).

Due to the internal friction of the cotton, most of the force was applied by these bottom members. The powered tramper provided approximately the same compression area as a conventional tramper. The area enclosed by the bottom of the housing in contact with the cotton is 175.3 cm (69 in.) by 35.6 cm (14 in.). Figure 5.2 clearly shows the auger housing on the full-scale prototype.

Figure 5.2. Full-scale prototype.

Cotton was conveyed to the center of the module by opposite-handed auger flighting on each side of the shaft spanning the width of the module builder. Two different diameters of flighting were used to achieve the desired distribution of cotton. The outside section of flighting on each side had a 22.9 cm (9 in.) diameter and pitch. Two full pitches of this helicoid flighting were used on each side for a total length of 45.7 cm (18 in.). Flighting with a 15.2 cm (6 in.) diameter and pitch was used for the inside section. One piece of 6.35 mm (0.25 in.) thick sectional flighting, with a 15.2 cm (6 in.) length, was used on each side.

The different diameters of flighting were used because the powered tramper does not need to convey all the cotton in the housing to the center. If cotton was moved completely to the center, a ridge would be formed in the center, but a flat region would exist on each side of this ridge. Problems with cotton plugging the housing would also likely result. With two different diameters of flighting, some cotton will exit the housing before reaching the center.

The auger flighting was mounted on steel pipe with an outside diameter of 7.303 cm and a thickness of 0.701 cm (2.5 in. schedule 80). Bushings were mounted inside the pipe, and the assembly was bolted to a 3.8 cm (1.5 in.) diameter shaft. The shaft was supported by bearings on each side of the auger housing and was powered by a hydraulic motor (Char-Lynn 103-1015) mounted at the bottom of one of the support columns. With a maximum continuous flow of 56.8 L min^{-1} (15 gal min^{-1}) and pressure drop of 10.3 MPa (1500 psi), this motor produced 390 N m (3450 lb in.) of torque at a speed of 183 min^{-1}. Power was transmitted to the shaft using #80 roller chain and an 11:15 sprocket ratio. The resulting maximum torque and speed of the auger shaft were 532 N m (4705 lb in.) and 134 min^{-1}.

One problem encountered during initial testing of the powered tramper in 2007 was cotton plugging in the central area of the housing. A drawing of the modified design is shown in figures 5.3 and 5.4. Cleanout paddles, 15.2 cm (6 in.) long, were mounted 90° behind the end of the auger flighting to push cotton out of the housing. A central diverter section was also modified to minimize clearance with the cleanout paddles. The diverter section tapers from the auger diameter at the outside to the diameter of the pipe in the center.

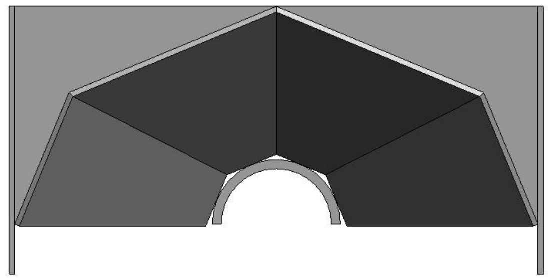

Figure 5.3. Side view of diverter section.

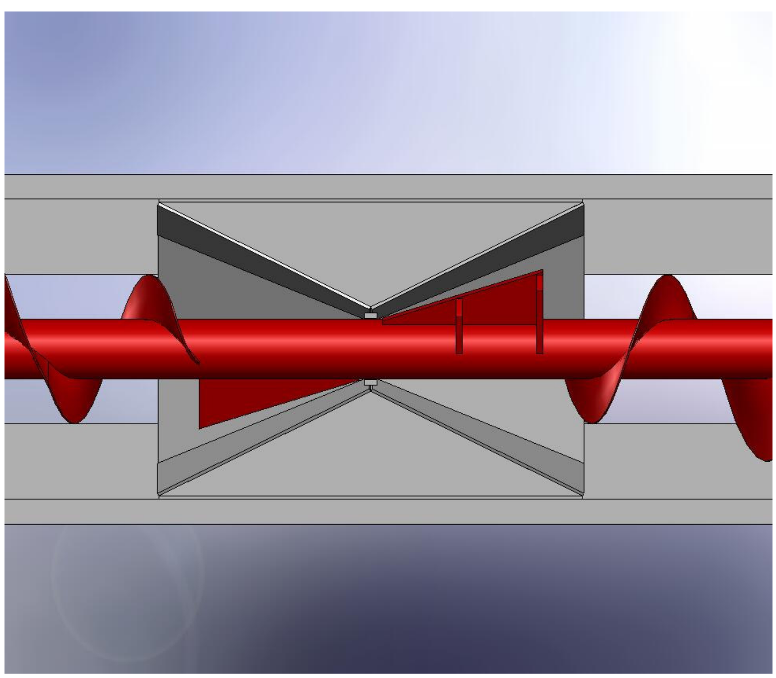

Figure 5.4. Bottom view of auger shaft and diverter section.

5.3.3. Hydraulic Design

To maintain the tramper hydraulic cylinder travel speed, the hydraulic motor was connected in series with the tramper cylinder (figure 5.5). When the tramper cylinder extended, the powered tramper operated until the pressure in the cylinder head reached the setpoint of the adjustable pressure switch. The pressure switch (United Electric Controls 10-D-13) was connected to a relay that energized the solenoid valve (Vickers SV1-16-C). Closing the pressure switch shifted the solenoid valve, which opened the bypass line around the motor, stopping the auger.

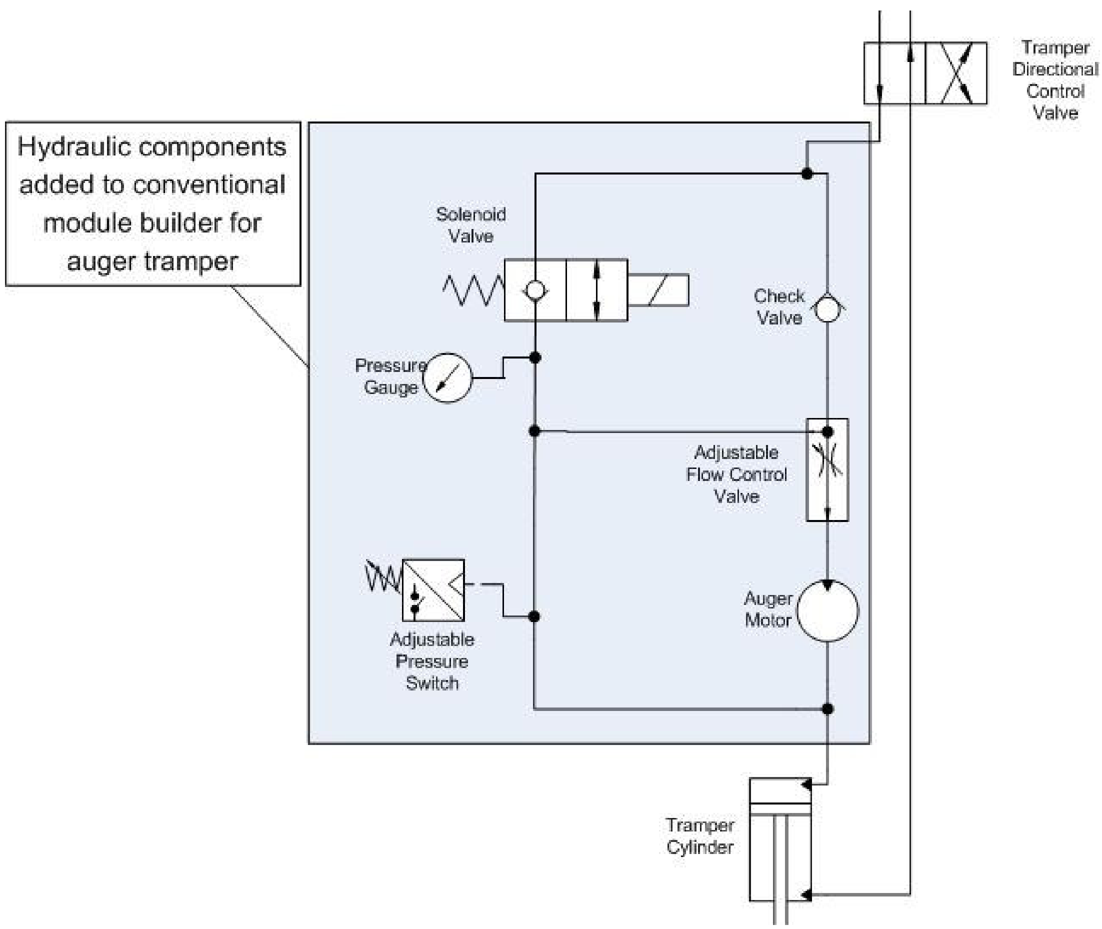

Figure 5.5. Powered tramper hydraulic circuit.

The auger must be shut off because cotton under compression could not be moved effectively and full pressure needed to be available for the tramping cylinder to generate maximum force. The operating principle behind this design is illustrated in figure 5.6. During the start of a compression stroke, the tramper cylinder does not require significant pressure. This period is also when cotton can be moved most effectively by the auger. The auger is turned off before maximum system pressure is reached, allowing full pressure to be supplied to the cylinder.

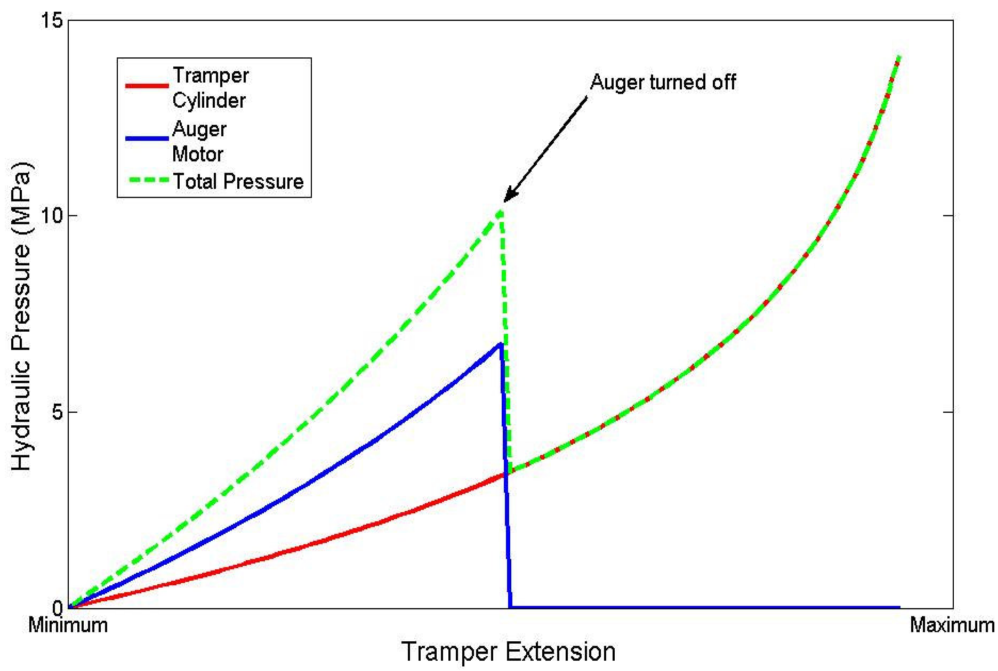

Figure 5.6. Operation of auger motor and tramper cylinder.

When the tramper was retracted, the check valve (Stauff RV167S) forced fluid to flow through the solenoid valve and prevented the auger from turning in reverse. An adjustable priority flow regulator (Integrated Hydraulics 2FP95) allowed the speed of the auger to be varied. An in-cab switch was wired in parallel with the pressure switch so the module builder operator could disable the powered tramper if desired. The operator may turn the powered tramper off on the last pass of the module to prevent loose cotton from being deposited on the surface of the module.

5.3.4. Testing

The powered tramper was installed on a 2005 model Crustbuster module builder with 3.35 m (11 ft) high sides and a chain-driven carriage. The module builder was equipped with an automatic tramping system. The powered tramper was used to build 12 modules in 2007. Optimal settings for the system parameters were determined. The pressure switch was set between 3.4 and 4.1 MPa (500-600 psi). This pressure setting was the highest value that would reliably ensure that the auger motor was bypassed before the maximum hydraulic system pressure (relief valve setting) was reached. The optimum auger speed was between 100 and 150 min^{-1}. Faster speeds resulted in increased plugging of cotton in the housing. As a result of this initial testing, the 11:15 sprocket ratio was selected. By allowing the full 56.8 L min^{-1} (15 gal min^{-1}) flow to the motor and using the sprocket ratio to decrease speed, the maximum amount of torque was generated.

Following the design modifications, testing continued in August 2008 in the El Campo, Texas area and September 2008 in the College Station, Texas area. Approximately 20 modules were constructed. 35 additional modules were built using the powered tramper from November 2008 to January 2009 near Anson, Texas. A module height measurement system was used to measure 28 modules– 10 were built using the powered tramper and 18 without. Five of the conventional modules were constructed using a different module builder and measured at the gin. The remaining 13 conventional modules were built with the experimental module builder; however, the powered tramper was shut off.

This height measurement system recorded the heights of multiple points on the top surface of the module. A module height surface was generated, with 15.24 cm (6 in.) resolution along the length and width of the module. This height surface was used to generate parameters describing the module surface that were used in a statistical analysis.

5.3.5. Evaluation

For each module, cross-sections across the width of the height surface were examined. The cross-sections were taken every 30.5 cm (12 in.), so the distance between sections was greater than the diameter of the auger. The area where water could collect was calculated for each cross-section. An analysis of variance was performed on the water collection area data using the generalized linear models procedure in SAS, *PROC GLM*. The tramper used, powered or conventional, was the main effect, while the module and measurement (for repeated measurements on the same module) were nested effects in the experimental design. The difference in mean water collection area between the powered and conventional tramper was compared.

Seven modules were measured after being covered during 22 m s^{-1} (50 mi hr^{-1}) winds. These modules appeared to have fewer depressions than modules that had just been constructed, regardless of the test conditions. As a result, a classification variable was included to distinguish these modules and used as a main effect in the statistical analysis. All other modules were measured before being covered. Table 5.1 displays the number of modules observed with each combination of treatments.

Table 5.1. Number of modules in each treatment group– powered tramper.

Treatment Combination	Number of Modules
Conventional	13
Conventional, Measured after Covering	5
Powered Tramper	8
Powered Tramper, Measured after Covering	2

5.4. RESULTS AND DISCUSSION

During testing in 2007, the powered tramper was observed to move cotton from the sides to the center of the module builder. Modules built using the system are shown in figure 5.7.

Figure 5.7. Modules built in 2007 using the powered tramper.

Although the auger moved cotton when in contact with the module surface, this was not the primary mode of action. When the powered tramper was raised after a compression stroke, cotton would be caught between the auger and the housing (figure 5.8). On the next compression stroke, the cotton was conveyed out of the housing closer to the center of the module. The cotton in the housing was collected from the side of the module with more cotton. After several passes compressing the cotton, a significant amount of cotton had been moved to the center, and the cotton was no longer collected in the auger housing between tramping strokes.

Figure 5.8. Cotton caught in auger housing after tramping stroke.

The importance of this method of moving cotton was verified when the original check valve failed (this valve was not large enough for the system flow rate). The powered tramper then rotated in reverse when the tramper was raised, so cotton was not trapped in the housing. The modules in figure 5.7 were representative of the modules constructed with the powered tramper. Modules constructed with the failed check valve were much higher on one side than the other. The harvester used unloaded cotton close to one side wall of the module builder. Without the functioning powered tramper, cotton was not moved, and the resulting module was significantly higher on the unloading side.

Testing in 2008 indicated that the current mechanical design performed satisfactorily. No problems with cotton plugging the housing were observed. Occasionally, a mass of cotton would remain in the housing for several tramping strokes, but the powered tramper would eventually clear the cotton from the housing without operator intervention. The auger flighting had sufficient mechanical strength, as no bending was observed during operation.

Modules constructed during August and September 2008 were also observed to have a crowned shape. Unfortunately, the module shape measurement system was not available to determine the shape of those modules. During testing near Anson, Texas, the module builder did not move cotton as effectively to the center of the module. Cotton did not remain in the housing after a compression stroke. Additionally, the auger did not turn during some compression strokes, particularly in cold weather when initially starting the module builder. Modules built during this testing are shown in figure 5.9.

Figure 5.9. Modules built in 2008 near Anson, Texas with powered tramper on.

Significant differences exist between these modules and the ones shown in figure 5.7. The modules in figure 5.9 had similar heights across the width, or were slightly higher on one side, while the modules in figure 5.7 have a higher region in the center of the module. Furthermore, the modules in figure 5.7 have a consistent height profile along the length of the module. In figure 5.9, large masses of cotton are present at corners of the module.

The module builder manufacturer indicated after testing that the selector valve on the module builder was not designed for the flow rates produced by the module builder hydraulic pump (Hornung, 2009). This selector valve receives fluid from the pump and directs the fluid to the valve block controlling the carriage and tramper or the valve block with the wheel and gate valves. The module builder operator manually selects the direction of fluid flow. Return flow from the selected valve block is also ported to the reservoir through the selector valve. The selector valve is used for safety reasons, since it prevents inadvertent operation of the wheels or gate while using the carriage or tramper and vice versa.

The module builder manufacturer indicated that this issue had been observed on multiple module builders. The primary symptom of this problem on conventional module builders was that the regeneration circuit that increased cylinder extension speed cycled on and off due to the additional resistance. This problem was first observed after several seasons of use and worsened over time, possibly due to a combination of oil contamination and the undersized valve. The malfunction of the regenerative circuit and a progressive increase in the severity of the problems were observed with the powered tramper module builder as well.

Since the improperly sized selector valve imposed a restriction in the return line, the pressure switch controlling operation of the powered tramper was actuated before significant cotton had been moved. Only a small amount of resistance by the cotton to the tramping cylinder was needed to stop the auger (possibly 700-1400 kPa pressure drop across cylinder, instead of 3400-4100 kPa). In cold weather, the viscosity of the hydraulic fluid increased significantly, resulting in a much larger pressure drop across the selector valve. If the magnitude of this pressure drop was larger than the pressure switch setpoint, the auger motor would always be off. An additional effect of this selector valve problem was that full pressure was not applied to the tramping cylinder due to the pressure drop across the selector valve.

Another problem observed during testing was failure of the shaft seal on the hydraulic motor. Because the motor was connected in series with the tramping cylinder, significant pressure was present at the outlet of the motor during compression of the cotton. Excessive motor case pressure resulted in failure of the shaft seal. This problem was likely exacerbated by the improperly sized selector valve on the module builder. The rapid cycling of the regeneration valve may have produced large pressure transients and damaged the motor shaft seal. Using a high-pressure shaft seal would prevent this problem.

5.4.1. Module Shape Evaluation

The ANOVA model was highly significant, with a p-value less than 0.0001. The interaction between the tramper and measurement condition (measured before or after covering) was not significant and was removed from the model. The results of tests of effects using the reduced model are shown in table 5.2.

Table 5.2. ANOVA tests of effects.

Effect	F-Statistic	P-Value
Tramper	1.44	0.2307
Measurement Condition	32.45	<0.0001
Module (nested)	7.10	<0.0001
Measurement (nested)	5.81	<0.0001

No significant differences were observed due to use of the powered tramper. The primary source of variation was the measurement condition. The modules that were measured after being covered during high winds had fewer depressions and a smaller mean water collection area, 110 cm^2, for the lateral cross-section, compared to 177 cm^2 for modules measured before covering. The force of wind on the cover compressed, and possibly moved, cotton on the top surface of the module. The repeated measurement effect is only significant because two measurements of one module resulted in mean water collection areas of 154 cm^2 and 474 cm^2. Removing one of these measurements from the data set made the measurement effect insignificant, since the other repeated measurements had similar mean areas.

The results obtained with the module measurement system agree with visual observations of the modules constructed. The powered tramper was not moving cotton effectively during the testing near Anson, Texas, and modules constructed with or without the powered tramper showed no significant differences. Previous testing had indicated that modules formed using the powered tramper had a peak in the center of the module, regardless of where cotton was unloaded. Modules built with a conventional tramper exhibited a peak where the cotton was unloaded, and this was shown in module surfaces developed from the measurement system data (figure 5.10).

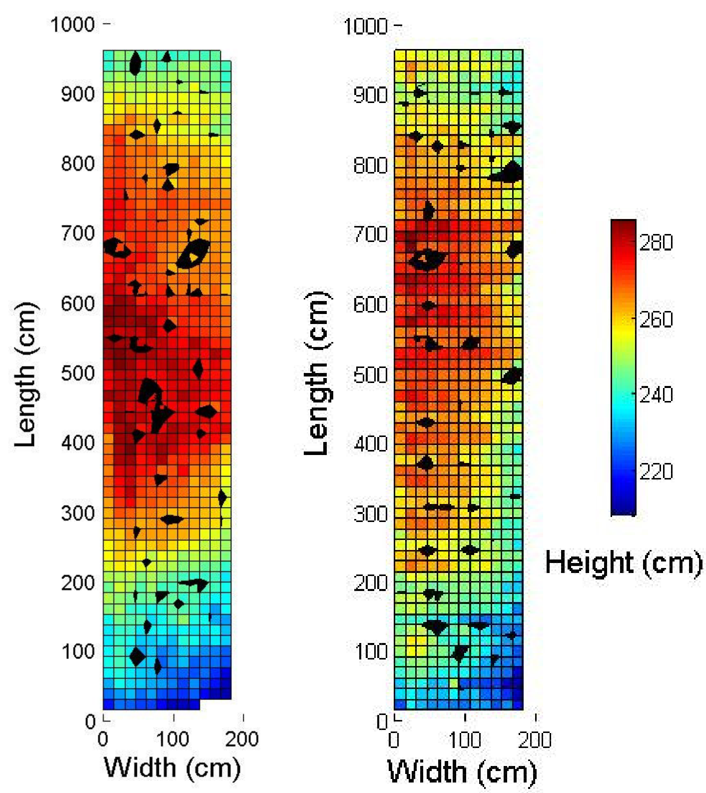

Figure 5.10. Surface of module built with powered tramper on (1b, on left) and module built with powered tramper off (28b, on right).

The module on the left was built with the powered tramper turned on, while the module on the right was constructed with the powered tramper off. Both modules were higher on the left side than the right side. This data indicated that the powered tramper was not functioning properly, likely due to the improperly sized selector valve.

5.5. CONCLUSIONS

The powered tramper automatically moved cotton from the sides of the module to the center, and the current design functioned without plugging, evidenced by visual observation of modules in 2007 and early 2008. Module height data collected in Anson, Texas in late 2008 and early 2009 indicated that the powered tramper did not improve module shape. This result was due to the improperly sized module builder selector valve. This valve caused the auger to turn off prematurely, and in some cases prevented rotation entirely. The cold temperatures during testing in Anson, Texas exacerbated this problem as the hydraulic fluid viscosity and the pressure drop across this valve increased. Further data on the performance of the powered tramper is needed with a correctly sized selector valve.

6. AUTONOMOUS MODULE FORMING SYSTEM

6.1. INTRODUCTION

Cotton harvesting requires a large labor force to operate harvesters, boll buggies, and module builders. Increasing labor costs and the difficulty in finding adequate labor have resulted in a demand for alternative harvesting systems with reduced labor requirements. Equipment manufacturers have developed systems to automatically build cotton modules on pickers (Gola et al., 2000; Covington et al., 2003b); however, these systems have several drawbacks.

Most notably, the on-board module builders are only available on pickers. During the 1994-1995 harvest season, 23% of the total volume of U.S. cotton, and 85% of Texas cotton was stripper harvested, primarily in the High Plains (Glade et al., 1996). While a greater proportion of producers are using pickers, a significant proportion of cotton in Texas remains stripper harvested. These producers currently have no options other than using conventional module builders.

Some producers utilizing cotton pickers may find that automating existing module builders is more economical then investing in pickers with on-board module builders. The pickers with on-board module builders cost over $100,000 more than the comparable conventional pickers. Retrofitting a module builder to autonomously build modules requires a much smaller investment than purchasing new pickers with on-board module builders.

Along with reducing labor needs, an autonomous module builder would also consistently build properly shaped modules that resist moisture penetration. Inexperienced workers often operate module builders, and the quality of module shapes produced varies. Operator fatigue and poor visibility can also contribute to the construction of poorly shaped modules. The modules produced with an autonomous module builder also have the advantage of using existing covers and gin equipment.

6.1.1. Objectives

This research developed from efforts to maintain cotton quality during storage in modules. The primary goal of this research was to develop an autonomous module forming system to reduce labor requirements during cotton harvesting while consistently building high quality modules. The main objectives of this research were:

- Develop algorithms for efficient movement of seed cotton in the module builder.
- Design a wireless communication system and boll buggy interface for control of the autonomous module forming system.
- Evaluate the autonomous module forming system performance by measuring module shapes and recording the time required to build modules.

6.2. LITERATURE REVIEW

The module system of storing and handling seed cotton was developed by Wilkes et al. (1974) in response to harvesting delays due to the unavailability of trailers. Shelby and Parish (1975) developed an automatic control system for the module builder. A basic leveling system was implemented, where the carriage was moved from the front to the rear of the module builder at a height set by the operator. This system used limit switches to detect when the carriage was at the front or rear.

After the leveling pass, the compaction cycle was started. A pressure switch was used to stop a compression stroke when the maximum pressure was achieved. Time delay relays were used to control the height the tramper was retracted and the distance between tramping strokes. The automatic system continued to compress the cotton until stopped by the operator. One drawback of this system was the rudimentary leveling action, which would likely not move enough cotton; move too much cotton, causing the carriage to stall; or move a large mass of cotton to the rear of the module builder. This leveling system would also not produce a crowned surface when finishing a module. Additionally, there would be wasted action from raising the tramper too high or making unnecessary compaction cycles.

Commercially available systems, based on the same system described by Shelby and Parish, exist for automating the compaction cycle. An additional retrofit system allows a boll buggy operator to level the cotton in the module builder (Module Automation Systems, 2009). A camera in the module builder transmits video to a monitor in the boll buggy cab, where the operator can level cotton manually or start the automatic system using a remote control. However, none of these systems automate the leveling process.

6.3. MATERIALS AND METHODS

6.3.1. Specifications

The autonomous module forming system should build modules without requiring a module builder operator. The only human interaction needed should be commands issued by the boll buggy operator during or immediately after unloading. Ideally, the wireless transceivers would be capable of maintaining contact between the module builder and the boll buggy at all times, but a minimum communication distance of 50 m (164 ft) is required.

Initially, the system will be designed for communication between only one module builder and one boll buggy. However, multiple machines are commonly used in harvesting cotton. Consequently, the wireless transceivers used should be capable of mesh networking– a network where every node can communicate with every other node.

The autonomous system program should be robustly designed so that the program does not get caught in a loop, regardless of operating conditions. If the program becomes stuck, cotton will not be compressed when the boll buggy returns to unload. Cotton can collect on the sides and easily be pushed out of the builder as the module nears completion. The autonomous system needs to be designed to handle this situation as satisfactorily as an experienced human operator.

The autonomous system must be capable of building modules as fast as experienced human operators to keep up with modern harvesting operations. This requires the design of movement algorithms to facilitate unloading of boll buggies. An algorithm for quickly packing cotton is also necessary, since boll buggies may not be able to empty an entire load when the module is nearly finished.

Modules built with the autonomous system need to have shapes that will prevent the collection of water on their top surfaces. This specification requires that the mass of cotton be greater in the center of the module builder than at the ends.

6.3.2. Design

Design of the system was based on the sequence of actions an experienced human operator would use to build a properly shaped module as rapidly as possible. Generally, significant compression of the cotton in a module builder does not occur until at least three harvester baskets are unloaded into the module builder. At this step, cotton is moved towards the ends of the module builder. This action creates a lower region of cotton in the center of the module to facilitate faster unloading of the boll buggy (or harvester). After the final load of cotton is placed in the module builder, cotton is moved back towards the center to produce a crowned module.

The operator can not immediately begin leveling as the module nears completion or cotton would be pushed out of the module builder. An experienced operator will move the carriage into the cotton, extend the tramper, and move the carriage in the opposite direction. This sequence compresses the cotton and creates a space where loose cotton can fall. After performing this action across the entire the length of the module builder, subsequent compressions will further increase the volume for unloading cotton. Hardware was selected to acquire the information needed to accomplish these tasks.

6.3.2.1. Hardware

The module builder used for this research was equipped with an automatic tramping system. This system included a High Country Tek DVC10 valve control module that was programmed to control valve actions based on the inputs to the module. The DVC10 module has eight digital inputs, three analog inputs, and three universal inputs. The universal inputs can function as digital or analog inputs, read rotational speed sensors or quadrature encoders, or operate as a counter. The DVC10 has six sourcing outputs, and three sinking pulse width modulation (PWM) outputs for controlling proportional valves. The DVC10 and related products were used for compatibility with the automatic tramping system.

Two additional modules, a DVC50 and a DVC70, were added to the system. The DVC50 is an expansion module providing additional inputs and outputs– eight digital inputs, four analog inputs, two universal inputs, six sourcing outputs, and three sinking PWM outputs. The DVC70 is a datalogging module that was used for debugging and evaluating the autonomous system. These modules were connected with the DVC10 on a controller area network (CAN) bus. The CAN bus provided reliable high-speed communication between controllers using a standard protocol. Another advantage of using a CAN-based system was that additional controllers could easily be added to the network.

Sauer-Danfoss PVG 32 solenoid valves controlled the carriage motor and tramper cylinder in the automatic tramping system and were also used with the autonomous system. Sensors included with the automatic tramping system were two

Pepperl+Fuchs 30 mm proximity sensors (model number NBB10-30GM50-E2-V1) for indexing carriage position to the front or rear of the module builder and a GP:50 model 1002-RX-2-AA pressure sensor for measuring system hydraulic pressure.

An operator feedback system had been installed to provide information about the position of the carriage and the height of the module (Hardin IV and Searcy, 2007). The autonomous system incorporated this information, so the same carriage position sensing apparatus and tramper position sensor were used with the autonomous system. The position sensing apparatus used inductive proximity sensors to record rotation of the carriage drive shaft. The tramper position was determined by using an ultrasonic sensor to detect a target plate mounted on the tramper support column.

The autonomous system also required knowledge of the level of cotton relative to the tramper, for both directing leveling actions and maximizing the speed of the compaction cycle. The ultrasonic sensor only provided the tramper position relative to the carriage. Thru-beam mode infrared photoelectric sensors (Pepperl+Fuchs ML17) were mounted on both sides of the tramper (figure 6.1). Cotton blocking a beam (front or rear of the tramper) indicated that the specified side of the tramper was in contact with the cotton in the module builder. The ultrasonic sensor could then be used to determine the height of the tramper relative to the cotton surface in the module builder.

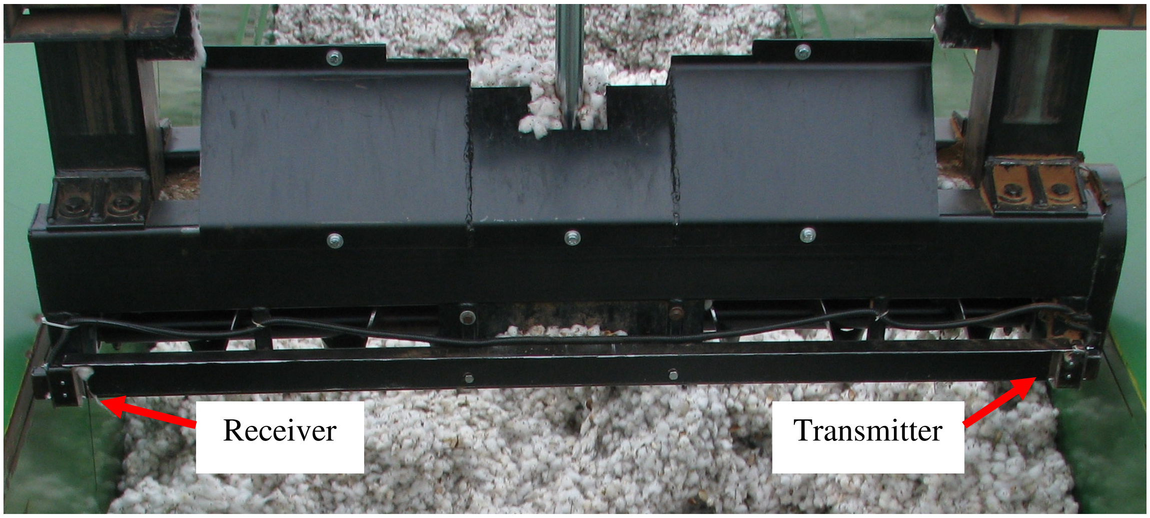

Figure 6.1. Tramper photoelectric sensor. This sensor pair was duplicated on the back side of the tramper.

The transmitters and receivers were mounted in housings constructed from 5.08 cm (2 in) x 7.62 cm (3 in) steel tubing with an acrylic cover to protect the sensors from both the applied mechanical force and cotton collecting around the sensor. The sensors were mounted on the ends of the tramper, 175 cm (69 in) apart. This sensor has a sensing range of 20 m; however, at this distance the excess gain of the sensor is over 200. The excess gain represents the ratio of the actual received signal strength to the minimum signal strength needed to cause an output by the receiver. An excess gain of at least 50 is recommended for very dirty environments (Banner, 2003).

Sensors were also needed to detect when the cotton level was high enough in the module builder that some compaction was needed before leveling. Retroreflective visible light photoelectric sensors (Banner World-Beam QS30) were mounted on all four corners of the module builder (figure 6.2). Banner BRT-92 x 92 reflectors were affixed to the carriage. The excess gain was approximately four at the maximum sensing distance of 9.75 m (32 ft). These sensors are not in contact with the cotton, so the sensor faces remained cleaner, and a large excess gain was not required. Additionally, increasing the excess gain at the maximum sensing range would have required laser photoelectric sensors, which are considerably more expensive than visible light and infrared sensors.

Figure 6.2. Photoelectric sensor and reflector for detecting cotton on sides of module builder.

A profile of the cotton surface after unloading was desired, without having to compress the cotton. A Sharp infrared distance measuring sensor, model number GP2Y0A700K0F, was mounted on top of the carriage and extended over the cotton in the module builder. This analog sensor had a measuring range of 100 to 550 cm (39 to 217 in.).

6.3.2.2. Wireless System and Display

Control of the automatic leveling system was done from the boll buggy tractor cab. The interface used was a 26.4 cm (10.4 in.) touch screen color graphic terminal (High Country Tek model D210). Touch screen buttons were provided for the operator to start and stop the automatic system. Additional buttons allowed the boll buggy operator to instruct the module builder to quickly pack a partial buggy load while waiting to unload the remainder (referred to as the quick tamp function), to finish the module regardless of the volume of cotton in the builder, and to manually control the valves. An image of the predicted module shape was also displayed to guide the operator in unloading cotton. Commands were also displayed, for example, if the module builder was ready to accept more cotton.

This display was designed to be connected to a DVC10 through a serial cable. Digi XBee-PRO 802.15.4 radio frequency (RF) modules wirelessly transmitted data between the DVC10 and the display. These RF modules receive serial data from the device they are connected to and transmit a packet of data according to the IEEE 802.15.4 protocol. Conversely, received RF packets are output to the connected device on the serial bus. These RF modules will form a mesh network, where any module can communicate with every other module in the network. This feature will allow multiple module builders and boll buggies to communicate in an extension of this system. These modules were selected because of this networking capability, their low cost, ease of implementation, and maximum outdoor line-of-sight range of 1.6 km (1 mi).

6.3.2.3. Algorithm

The autonomous module program was implemented using High Country Tek's Intella software, a proprietary development environment used with the DVC10 modules. This software was programmed by defining various program states. The system could perform certain actions upon entering a state or would repeat a set of actions as long as the program remained in that state. Transitions between states were also defined, generally based on sensor values or timers.

An overview of the algorithm used to build modules is shown in figure 6.3. When the automatic system was initially started, the tramper was retracted, and the carriage was moved to the front of the builder if it was not already at one end. The program is initiated with a command entered by the boll buggy operator. The operator instructed the module builder to perform a quick tamp or start the automatic system. Starting the automatic system initiated a scan of the module surface. The carriage traversed the builder and the height of the cotton was recorded at periodic intervals by the infrared distance measuring sensor.

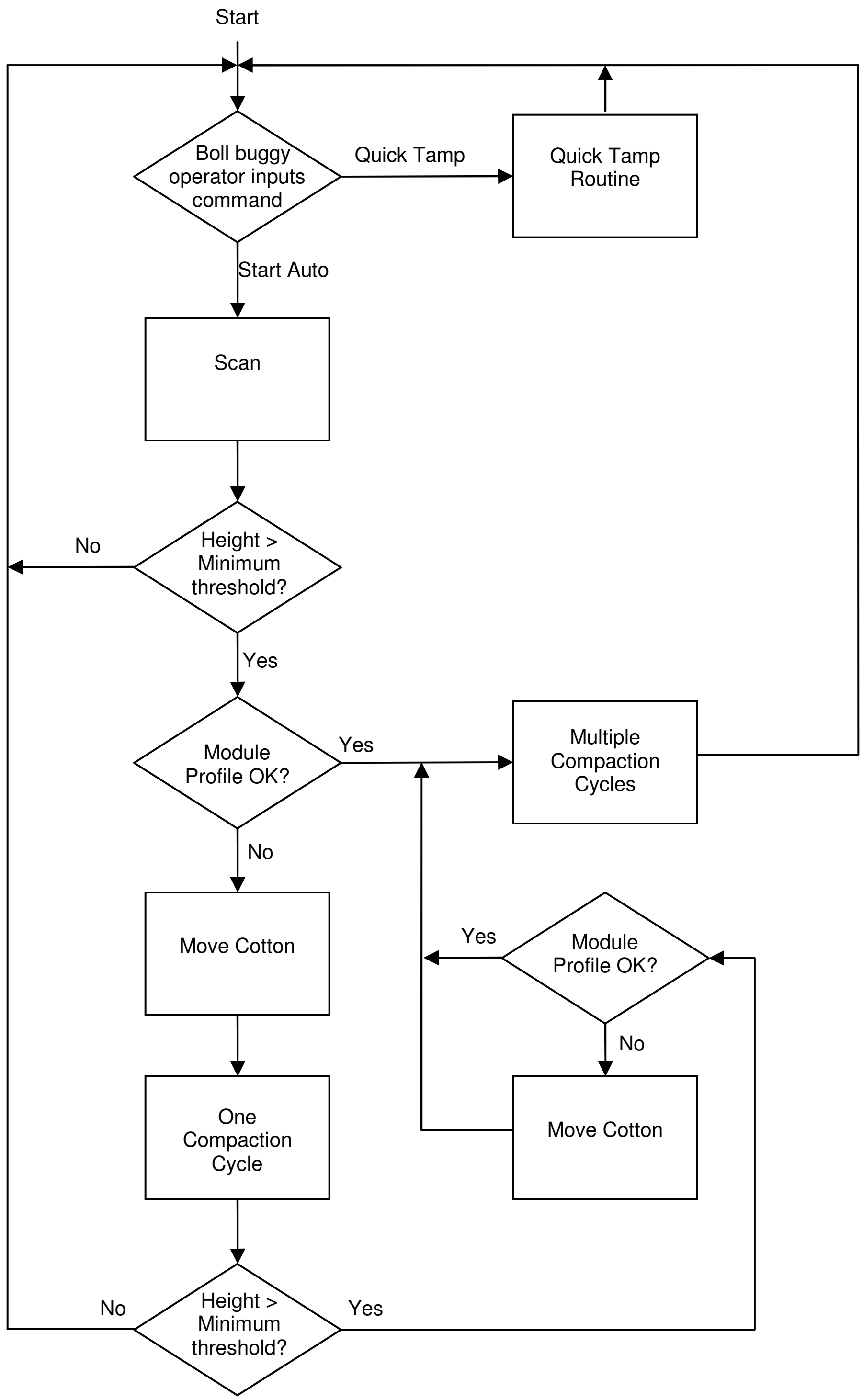

Figure 6.3. Automatic leveling system flowchart.

If the average height was less than a minimum threshold, the system stopped and waited for additional loads of cotton before proceeding. With a sufficient volume of cotton in the module builder, the module profile was examined. The desired profile was dependent on the volume of cotton. For an average height less than a maximum threshold, more cotton should be present at the ends of the module builder than in the center. If the average height was greater than the maximum threshold or the boll buggy operator pressed the finish button, no additional cotton will be added and the module should have a crowned surface. An acceptable module profile resulted in five compaction cycles for an unfinished module or seven compaction cycles for the final load.

An undesirable module profile resulted in the system moving cotton towards the ends for intermediate heights or towards the center to finish the module. One compaction cycle was performed and the average height and profile were reexamined. In this step, the compressed height determined with the ultrasonic sensor was used since this parameter is the most accurate predictor of module shape. Cotton was moved one additional time, if necessary. Five compaction cycles were performed after the final cycle of moving cotton for unfinished modules and seven compaction cycles for a finished module. After the compaction cycles were finished, the system stopped with the carriage at one end and waited for another command from the boll buggy operator.

6.3.2.3.1 Moving Cotton to the Ends

Cotton was moved from the center to the ends in three steps on each side (figure 6.4). This figure illustrates the sequence of movement actions taken if the carriage began the sequence on the left side of the module builder depicted below. Experience building modules indicated that cotton could not be pushed efficiently from the center in only one step, and three steps optimized the movement of cotton to the ends. Cotton was not pushed completely to the ends, as this resulted in modules that were higher at the ends than in the regions immediately adjacent. The steps were started one-third of the distance between the stopping point and the center, two-thirds of the distance, and at the center.

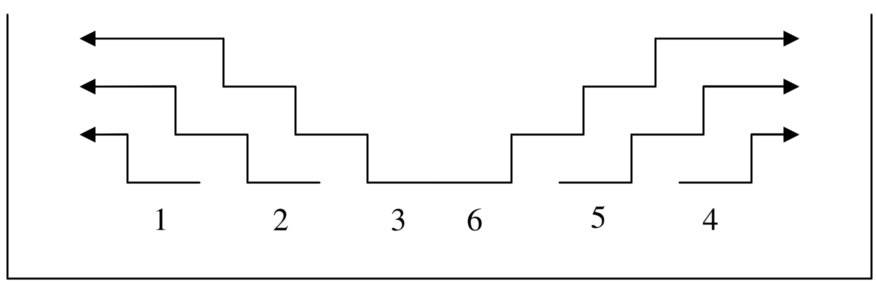

Figure 6.4. Sequence of actions in moving cotton to ends.

The stairstep action of the carriage and tramper did not necessarily proceed as shown, but was controlled by sensors. Each step began by moving the carriage to the desired location. The photoelectric sensors on the tramper and the ultrasonic sensor were used to lower the tramper a certain distance into the cotton. The carriage moved until the system pressure rose above a threshold specified in software. The tramper was raised a specified distance, and the carriage moved again. If the photoelectric sensors on the tramper detected that the side of the tramper in the direction of movement was not in contact with the cotton, the tramper was lowered back into the cotton before carriage movement continued.

6.3.2.3.2 Moving Cotton to the Center

The method of moving cotton to the center was a reversed version of the technique employed to move cotton to the end (figure 6.5), with the same sensor package used to control movement. The carriage stopped short of the module builder center during each movement action as this would push cotton into the other half of the module builder. The starting points are one-third of the distance between the stopping point and the end, two-thirds of the distance, and the end of the module builder. After cotton has been moved on one side of the builder, the cotton was compressed (steps four and eight). Compression strokes were started at the center and continued towards the end cotton was moved from. This action was added because the tramper would not clear the uncompressed cotton in the center.

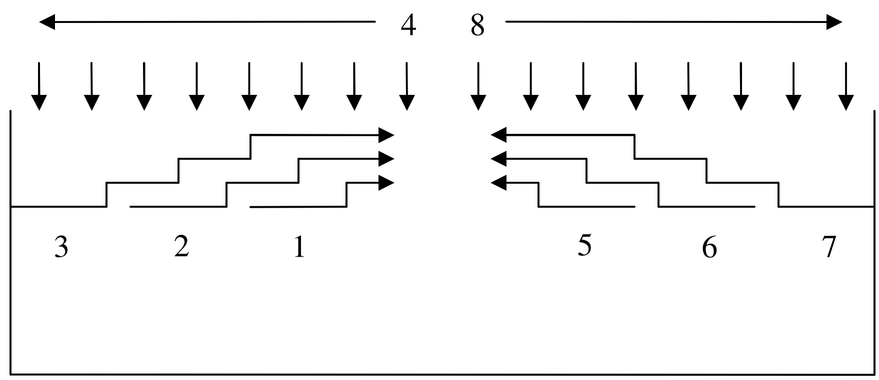

Figure 6.5. Sequence of actions in moving cotton to the center.

6.3.2.3.3. Compaction Cycle

The compaction cycle was performed after moving cotton and during the quick tamp routine. A compaction cycle consisted of tramping the cotton from the starting end of the module builder to the opposite end. The tramper was extended into the cotton until the maximum pressure was detected by the pressure sensor. The tramper was retracted while the photoelectric sensor on the side of the tramper in the direction of movement was blocked by cotton. After the tramper had cleared the cotton, the tramper was raised a programmed distance above the cotton. The carriage then moved to the location of the next tramping stroke. The system was programmed to make approximately 15 tramping strokes during one pass across the module.

6.3.2.3.4. Quick Tamp

The quick tamp function was added because it was not possible to create a large enough void in the center of the module to handle a full boll buggy basket when finishing a module. The quick tamp function also used the photoelectric sensors mounted on the tramper to determine when the tramper contacts the cotton. Simply compressing the cotton was not desirable because the tramper, even if fully retracted, pushed cotton in the direction of movement and eventually out of the end of the module builder. The carriage was moved with the tramper fully retracted a specified distance into the cotton. The tramper then extended a programmed distance, followed by a carriage movement in the opposite direction. Loose cotton fell into the void created by this action. The tramper was raised and this cycle repeated until the carriage reached the opposite end. One compaction cycle was then completed to create more space to unload cotton.

6.3.2.3.5. Cotton Detected on Sides of Module Builder

Cotton overhanging the sides of the module builder was detected by the photoelectric sensors mounted on the corners of the builder. If cotton was present on the sides of the builder during the initial scan, the system performed the same action as the quick tamp routine, although compression was not done when the carriage reached the opposite end of the module builder.

If cotton was pushed onto the sides of the module builder while moving cotton to the ends or the center, the carriage was stopped. Compression strokes were done in the direction of movement until the cotton no longer blocked the photoelectric sensors. The process of moving cotton was resumed at this point.

6.3.3. Testing

Two cotton modules were obtained from a gin to use during the initial development of the autonomous system during the spring and early summer of 2008. These modules were repeatedly broken apart and placed in a boll buggy using a loader tractor. During this initial testing and development, sensors were installed and the basic algorithm for moving cotton was developed.

The autonomous system was first tested during harvesting on several farms near El Campo, Texas in August 2008. The quick tamp routine was added so the boll buggies could unload rapidly. Different parameter settings were tested to optimize the module shapes constructed and the speed of the automatic system.

Continued testing was done at the Texas A&M IMPACT Center near College Station, Texas in September 2008. The display and wireless connection were first used here. A boll buggy was not used during harvesting, so the system was controlled remotely from a truck. The system generally functioned as desired, building modules without an operator present on the module builder.

Additional testing of the autonomous system was performed on several farms near Anson, Texas from November 2008 to January 2009. The wireless display was installed in the boll buggy tractor cab, and boll buggy operators were instructed on the use of the autonomous system. Approximately 50 modules were built automatically with 5 different boll buggy operators. Cotton producers in this area indicated a preference for modules with a more level top surface. Program parameters were modified so the profile of cotton was always judged to be acceptable after the final boll buggy load was added. This change prevented cotton from being pushed to the center.

A module height measurement system was used to record heights for 28 of the modules built near Anson, Texas. The autonomous system was used to build 16 of these modules. The height measurement system generated a module height surface with 15.24 cm (6 in.) resolution laterally and longitudinally.

6.3.4. Evaluation

Parameters generated from the module height surface included the total depression volume, number of depressions, average depression volume, maximum depression volume, average depression depth, average depression surface area, the water collection area in a profile of average heights along the length, and the water collection area in a profile of average heights across the width.

These parameters from analyzing the module height data were used as dependent variables in an analysis of variance (ANOVA). The ANOVA model included use of the autonomous system as a main effect. An additional independent effect was added to the model to distinguish modules that were measured after being covered during 22 m s^{-1} (50 mi hr^{-1}) winds. While collecting data, these modules appeared to have fewer depressions; therefore, a classification variable was included to distinguish these modules. All other modules were measured before being covered. The number of modules in each treatment group is shown in table 6.1.

Table 6.1. Number of modules in each treatment group– autonomous system.

Treatment Combination	**Number of Modules**
Conventional	7
Conventional, Measured after Covering	5
Autonomous	14
Autonomous, Measured after Covering	2

The generalized linear models procedure in SAS, *PROC GLM*, was used for the statistical analysis (SAS, 2004). An ANOVA was performed using a model with both main effects (autonomous system and measurement condition) and the interaction. For dependent variables with significant differences but an insignificant interaction effect, the ANOVA was performed again with only main effects. Least-squares means were calculated using the *LSMEANS* statement in SAS with the *PDIFF* option.

The time required for different actions of the automatic system was recorded for eight modules to verify that the system could operate without increasing harvesting time. Users of the autonomous system were asked to provide their feedback regarding the speed of the system, quality of modules built, ease of operation, and interest in the system as a commercial product.

6.4. RESULTS AND DISCUSSION

Efficient movement algorithms were designed during initial system development in summer 2008 in College Station, Texas using two modules that were repeatedly torn apart and rebuilt. Approximately 15 modules were constructed near El Campo, Texas. The autonomous system successfully distributed cotton in the module builder and the algorithms for the quick tamp routine and moving cotton from the sides of the module builder were developed. An additional eight modules were built near College Station, Texas. The wireless system and display were initially tested, and modules were formed autonomously. Approximately 50 modules were built near Anson, Texas entirely with the autonomous system by five boll buggy operators. Height measurements and timing data were collected on these modules.

6.4.1. Module Shape Evaluation

The results of the ANOVA, with a full model including the effects of autonomous system use, measurement condition (before or after covering), and their interaction are shown in table 6.2. Significant differences between treatment combinations were observed for all three dependent variables with a significant ANOVA model (highlighted in bold).

Table 6.2. Analysis of variance table for all dependent variables.

Dependent Variable	F-Statistic	P-Value
Total Depression Volume	1.41	0.2651
Number of Depressions	**18.72**	**<0.0001**
Average Depression Volume	0.38	0.7706
Maximum Depression Volume	0.64	0.5981
Average Depression Depth	**3.77**	**0.0239**
Average Depression Surface Area	1.70	0.1932
Water Collection Area- Length Profile	**6.52**	**0.0022**
Water Collection Area- Width Profile	1.05	0.3886

Use of the autonomous system, the measurement condition, and the interaction all had significant effects on the number of depressions. The least-squares means for the number of depressions per module were 43.6 when built manually, compared to 32.6 for modules formed autonomously. The modules that had been covered during significant winds before measuring also exhibited a significant decrease in the least-squares means for the number of depressions, from 47.5 to 28.8.

While the statistical analysis indicated that the autonomous system had an effect on the average depression depth, all modules measured before covering had similar average depression depths. The least-squares means for average depression depth are shown in table 6.3. Means followed by the same letter are not significantly different at the 5% level.

Table 6.3. Least-squares means for average depression depth.

Treatments	**Average Depression Depth (cm)**
Conventional	1.98[a]
Conventional, Measured after Covering	1.35[a]
Autonomous	1.98[a]
Autonomous, Measured after Covering	3.07[b]

This effect of the autonomous system on the average depression depth was due to the two modules built using the autonomous system that were measured after covering. These modules had a significantly larger average depression depth than all other groups of modules because they had fewer small depressions. Eliminating the interaction term from the model caused the ANOVA for average depression depth to be insignificant.

Furthermore, the small depressions that were present on other modules and eliminated by the wind compressing the cover against the modules are not likely to affect cotton quality. The cover will compress the cotton, possibly eliminating these depressions. Any water that could collect in these small depressions would likely not penetrate the cotton due to the wind moving the cover or evaporation.

The autonomous system and measurement condition also had a significant effect on the water collection area calculated for the average height along the length. The interaction term was not significant, and the ANOVA was performed using a model with only main effects. The autonomous system had a mean water collection area of 1179 cm^2, significantly less than the mean area of 3273 cm^2 observed with modules constructed manually. Modules measured after covering had a mean area of 760 cm^2, compared to 3692 cm^2 for modules measured before.

A comparison of the surfaces of a conventionally built module and a module built with the automatic system is shown in figure 6.6, and the average heights along the length are shown in figure 6.7 (only the top 1 m of the profile is shown). Some conventional modules, such as the following one, will contain lower regions in the center, depending on the operator's actions. As long as the final load contains enough cotton (generally one stripper basket), the automatic system will produce a module that does not contain lower regions in the center.

The module formed autonomously in figures 6.6 and 6.7 was significantly higher at one end because the boll buggy operator repeatedly unloaded cotton at that end of the module. This shape was extreme for the autonomous system, as most modules built automatically had a peak closer to the center and less variation in module heights. However, this shape would be preferable to the shape of the module built by a human operator displayed in figures 6.6 and 6.7. Since the total depression volumes and values of other parameters describing the surface depressions for these modules were similar, the water collection area along the length profile provided a better indicator of this difference in shapes.

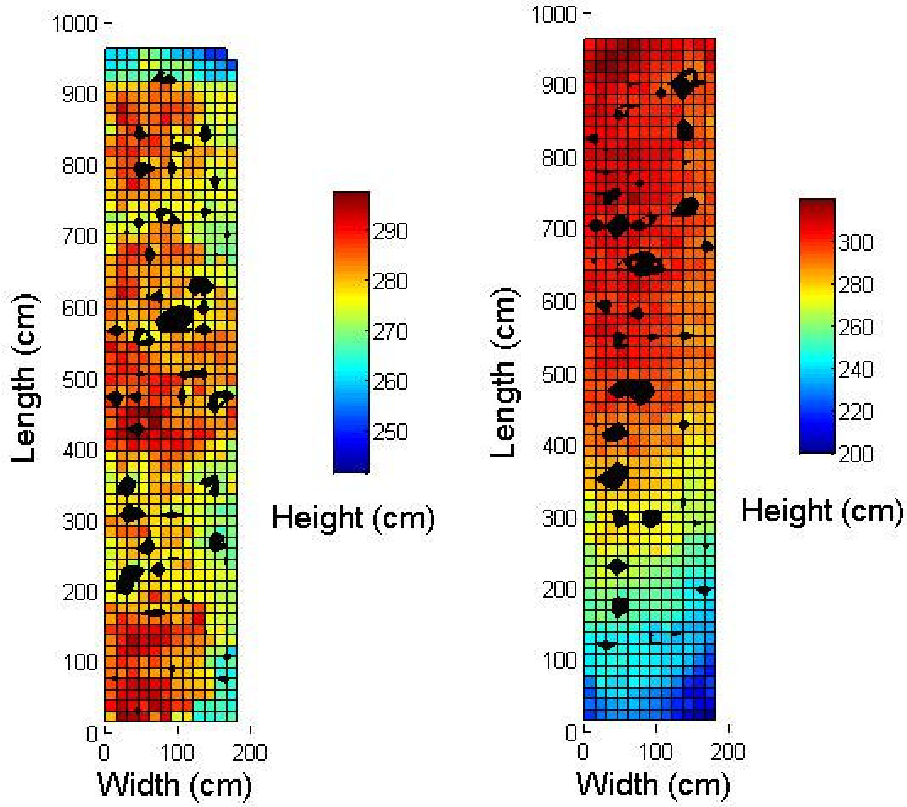

Figure 6.6. Surface of conventionally built module (18c, on left, depression volume = 12.4 L) and autonomously built module (26, on right, depression volume = 15.5 L).

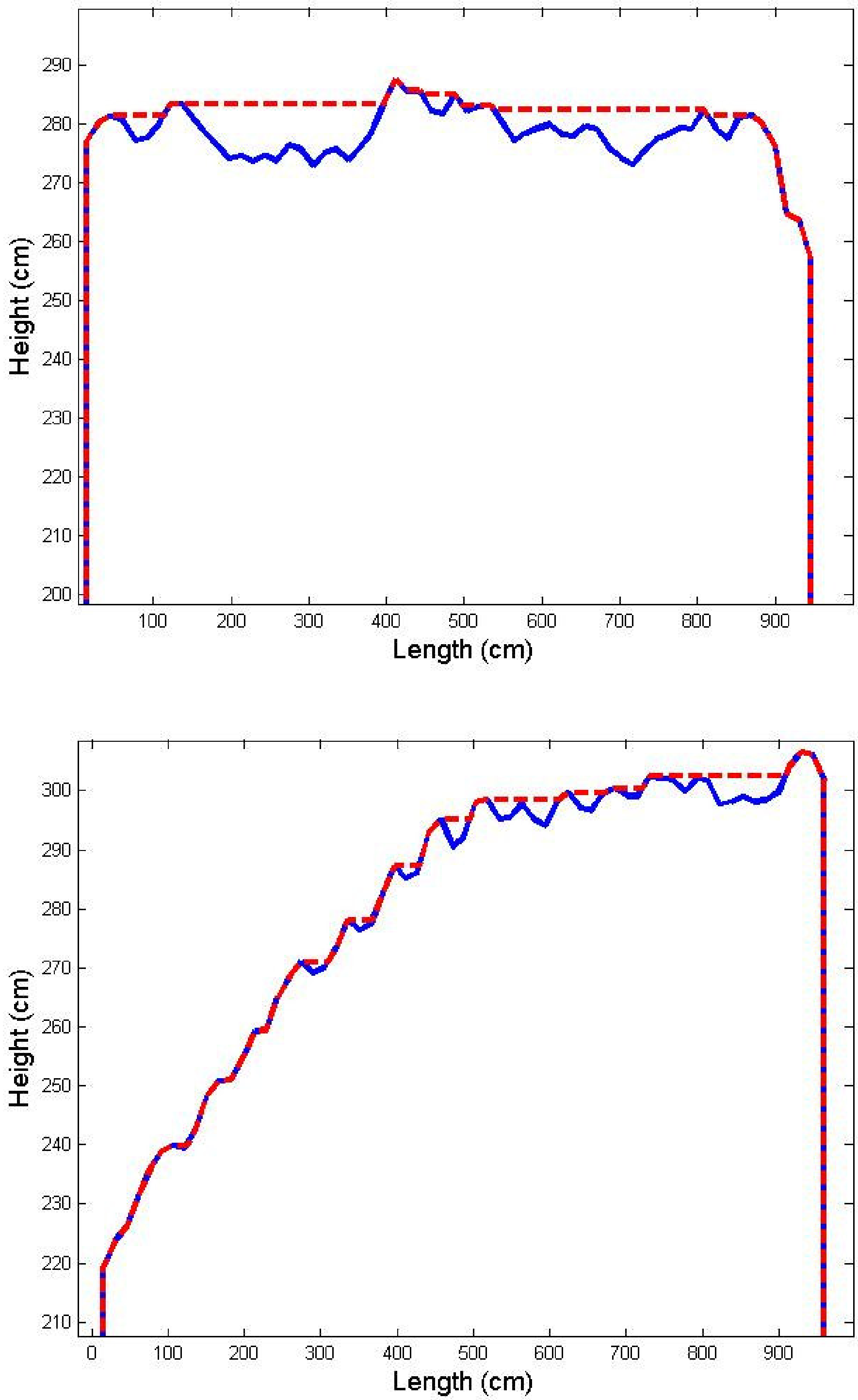

Figure 6.7. Average height along the length of a conventionally built module (18c, top, water collection area = 3420 cm^2) and a module built with the automatic system (26, bottom, water collection area = 975 cm^2).

6.4.2. Automatic System Operating Time

Timing data for the autonomous system was collected while used with an eight-row stripper, a four-row stripper, and a boll buggy. When fully operational, the autonomous system did not cause any delays in harvesting, although cotton yields were generally 3.7 bales ha^{-1} (1.5 bale $acre^{-1}$) or less. Previous testing was done using the autonomous module builder with two eight-row strippers, two boll buggies, and two conventional module builders in cotton yielding over 4.9 bales ha^{-1} (2 bale $acre^{-1}$). No delay in harvesting due to the autonomous system was observed during this testing.

The user was able to select three modes of operation– normal leveling and compaction, quick tamp, or finishing the module. The mean times for each phase of operation are displayed in table 6.4. The normal operation average only includes passes where all leveling and compression cycles were completed, excluding data where the system stopped automatically due to a low level of cotton in the module builder or manually to unload cotton.

Table 6.4. Mean times for different automatic system operations.

Operation	Time (s)
Normal	603
Quick Tamp	136
Finishing	486

Normal operation began with actions to compress cotton near the sides of the module builder. Due to a misalignment of one of the photoelectric sensor used to detect high levels of cotton, the compression of high levels of cotton was sometimes performed unnecessarily. The average time for this step during normal operation was 37 s; however, the average time would likely have been longer with a properly aligned sensor. If this operation was performed due to the misaligned sensor, and not the presence of cotton on the sides of the module builder, only 15-20 s were required. Compression of high levels of cotton was followed by a scan to measure the height of cotton along the length of the module. The scan step required an average of 10 s to complete and also proved unnecessary, as the distance measuring sensor utilized in this step was not accurate. Eliminating the scan step and the erroneous initial compression due to the misaligned sensor would likely decrease the total time required to build a module by slightly more than one minute.

During all observations of the system, both passes of moving cotton to the ends were actually performed. The second movement pass was likely unnecessary on some occasions, increasing the time required to build the module. The first movement pass was completed in a mean time of 66 s, while the second pass required an average of 76 s to complete. The second movement pass required more time since the system was attempting to move already compacted cotton.

The time required to complete a compression cycle before the final boll buggy load was added decreased from 79 s for the first compression pass to 67 s for the final compression pass, as the distance the tramper was raised decreased. Similar times were observed for compression after the final load was added. The mean time for these compression cycles decreased from 77 s for the initial cycle to 61 s for the final cycle.

These cycle times were affected by the regeneration valve settings. Due to an improperly sized selector valve on the module builder, the regeneration circuit typically cycled on and off, resulting in undesirable operation. The regeneration valve could be adjusted so that no regenerative flow occurred, preventing rough operation, but increasing cycle times.

The module builder algorithm was designed so that the autonomous system would stop after the initial compression pass if the tramper can be fully extended. The algorithm worked as designed during testing. The average time required for this operation was 161 s.

The quick tamp routine required an average of 136 s to complete and typically did not have to be used for unloading the first three or four harvester baskets. For the five modules containing six harvester baskets, the boll buggy operator ran the quick tamp routine between two and four times, with an average of 2.6. For the three modules with five harvester baskets, the quick tamp routine was not used on two of the modules, and was used three times on the other module. This module initially had three harvester baskets unloaded before any compression was done, requiring the quick tamp to be run once; the quick tamp function was also used twice on the final harvester load.

Four of the modules containing six harvester baskets had complete timing data to calculate the total time the automated system was operating. These times ranged from 34.8 to 39.5 min, with an average of 37.4 min. This time did not include any time required to unload boll buggies. Three of these modules had the cotton delivered in four boll buggy loads. The remaining module received five boll buggy loads; however, two of these loads occurred in rapid succession and the automated system was stopped by the boll buggy operator before significant operating time elapsed. The variation in time was primarily due to the number of quick tamp routines that were performed by the boll buggy operator. Improvements to the autonomous system and an optimal pattern of unloading by boll buggies could resulted in an expected operating times as low as 30.5 min.

The maximum yield that could be harvested without exceeding the module building rate of the autonomous system was determined. This analysis assumed that a producer has one module builder per harvester and enough boll buggies so the harvesters do not have to wait to unload. Typical harvest efficiencies for cotton pickers are 70% (ASABE, 2006). Because stripper harvesters generally have similar downtimes for turning and unloading, the same harvest efficiency can be used. Harvesting speeds of 6.4 km hr^{-1} (4.0 mi hr^{-1}) for a six-row picker and 6.0 km hr^{-1} (3.7 mi hr^{-1}) for an eight-row stripper were used (John Deere, 2009). A turnout of 35% is commonly observed with picker-harvested cotton and 30% is a typical value for stripper-harvested cotton.

One module, with an estimated mass of 9980 kg (22000 lb) can be built by the automatic system in an average of 37.4 minutes. An estimated 10 additional minutes is required for unloading boll buggies, and moving from a finished module to the next location. A six-row picker operating on 102 cm (40 in.) rows will harvest this mass of seed cotton in 47.4 minutes if the average yield is 7.39 bales ha^{-1} (2.99 bales $acre^{-1}$). The yield that matches module builder capacity with an eight-row stripper is 5.14 bales ha^{-1} (2.08 bales $acre^{-1}$). The average U.S. yield was 4.2 bales ha^{-1} (1.7 bales $acre^{-1}$) in 2008, while the average Texas yield was 3.4 bales ha^{-1} (1.4 bales $acre^{-1}$) (USDA-NASS, 2009). The estimates are conservative, as 76 cm (30 in.) rows are commonly used and modules can be built larger than 9980 kg (22000 lb). Optimizing the autonomous system program and the unloading of boll buggies should enable the system to operate faster. The autonomous module forming system should not cause any delays during harvesting.

6.4.3. Autonomous System Operation

This final prototype functioned well, with the only cause of total system failure due to breakage of the cable to the photoelectric sensors on the tramper. Improved routing and protection of this cable should eliminate this problem.

One cause of minor system malfunction was misalignment of the photoelectric sensors on the corners of the module builder with the reflectors on the carriage. This problem occurred twice during testing, and the sensors were subsequently realigned. A different sensing technique may be more suitable for detecting cotton on the edges of the module builder. For instance, mechanical sensors could be mounted on the carriage that output a control signal when cotton was contacted.

The photoelectric sensors on the tramper also were blocked once by dirt and leaf particles that filled the housings where these sensors were mounted. Proper sealing of these housings would prevent the ingress of this material. An additional operational concern arose from an improperly sized selector valve on the module builder. When initially compressing cotton, the tramper was not raised high enough. This was not due to an actual issue with the autonomous system. An excessive pressure drop across the selector valve caused the pressure sensor to record the maximum system pressure of 13.8 MPa (2000 psi) before the tramper was fully retracted. This high pressure reading caused retraction to stop, and loose cotton was pushed by the tramper.

The system functioned well, regardless of the location that cotton was unloaded. If the cotton was primarily unloaded at one end of the module builder, the resulting shape would be similar to the module constructed autonomously in figures 6.6 and 6.7. This shape will prevent water collection and no effect of unloading location on operating speed was observed.

As a result of the system modification to prevent cotton from being pushed towards the center on the final pass, the location and quantity of the final load of cotton affected the final shape of the module. Generally, one full stripper basket needed to be placed near the center of the module to produce a crowned shape. Furthermore, cotton unloaded at one end of a nearly finished module also posed a problem. In one instance, an eight-row stripper unloaded directly into the module builder. This action required the stripper to back up beside the module builder and unload at the rear. However, this scenario would pose a problem for a conventional operator as well, since cotton can not be moved from areas adjacent to the ends.

The wireless connection was generally only reliable when the boll buggy was stopped to unload at the module builder, although the module builder was controlled from a maximum of 400 m (1300 ft). This result was due to the architecture of the DVC system, since the DVC10 and display were not designed to be used over a wireless connection. The DVC10 controlled the display by sending large strings of data (greater than 1000 characters) over the wireless serial connection. All information displayed was resent from the DVC10 every 10 ms.

Due to the large amount of information sent with no error detection and correction, one missing bit could result in the display not functioning properly. The wireless transceivers were capable of transmitting a significant portion of the messages correctly, but without any error correction, the display often malfunctioned at larger distances.

The wireless interface proved satisfactory for the initial development of the system. Reliable control of the module builder was achieved when the boll buggy was unloading next to the builder. The future extension of the autonomous system to a harvesting scenario with multiple machines will require greater range. A boll buggy will need to be directed to the appropriate module builder while in the field. Alternative boll buggy interfaces are available that should be more suited to wireless data transmission.

Certain aspects of the algorithm were determined to be unnecessary. The infrared distance sensor used during the initial scan was not accurate and the autonomous system functioned well without its use. The second set of actions to move cotton to the ends of the module builder after unloading were likely ineffective. Eliminating this step could significantly increase the speed of building modules.

6.4.4. Acceptability of Autonomous System

Multiple boll buggy operators were trained to use the autonomous system. The simple interface with four commands was easily understood. Operators were able to use the interface after training on a limited number of modules. The major problem with this interface was that the display was not designed for wireless communication. This resulted in display errors, a lack of response to user input, and a more limited range of the wireless data transmission system. A simpler interface should function satisfactorily over a wireless serial connection. Harvesting crew supervisors commented that the system worked well and would be useful in addressing the difficulty in finding adequate labor.

6.5. CONCLUSIONS

The autonomous module forming system was reliable and simple for the boll buggy operators to use. The algorithms for moving and compressing cotton were successful, regardless of loading conditions. Cotton could be unloaded in any reasonable manner (for instance, unloading all cotton at one end would likely not produce a desirable module) and a well-shaped module was built. The autonomous system pushed no more cotton out of the module builder while moving cotton than an experienced human operator would. The primary reliability issue was due to cable breakage, a problem that can easily be addressed by improved cable routing and protection.

The autonomous system built modules with more desirable shapes than a human operator. Use of the autonomous system reduced the water collection area over the length by 64%, from 3273 cm^2 to 1179 cm^2. The mean number of depressions was decreased from 43.6 to 32.6. If at least one harvester basket of cotton was in the final load, modules built with the autonomous system did not have any low regions when viewed from the side. Building a properly crowned module only required that the boll buggy operator select the autonomous system command to finish the module when the final full harvester basket is unloaded. If a partial basket is harvested or cotton is vacuumed off the ground, the finish command should be selected for both the previous load (the final full basket) and the final load containing a small amount of cotton.

The time required to build modules with the autonomous system was comparable to the time needed for an experienced human operator to build a module. A mean operating time of slightly over 37 minutes was observed during testing. The system was used with an eight-row stripper, a four-row stripper, and one boll buggy without delaying harvesting, although cotton yields were generally low. Other testing was conducted where the automatic module builder was used with two eight-row strippers, two boll buggies, and two conventional module builders. Some higher yielding cotton (>4.9 bales ha^{-1}) was harvested in this scenario. Again, no delays in harvesting operations due to the module builder were observed.

The autonomous module forming system could result in significant savings with little additional investment in equipment. The commercially available automatic tramping system contained the control hardware and some sensors needed for implementation of the automated leveling system. Nine additional sensors, costing approximately $620, were also required. The cost of the wireless transceivers and a simplified interface would be an additional $500. The autonomous system will completely eliminate one equipment operator and may build better quality modules.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

This research has led to the development of systems that can improve module shape and reduce the labor necessary to build cotton modules. An operator feedback system was developed that accurately predicted module shape. The system correctly identified 75% of tramping strokes and simple modifications could increase the success rate above 90%. Two-thirds of predicted height values were within 7.62 cm (3 in.) of the measured height, even though the measurement technique had significant inaccuracy.

This display was used by operators to inform decisions about where to move cotton in the module and to direct the unloading of boll buggies. Operators found that the display was particularly useful in low visibility situations, such as at night or when moving cotton at the far end of the module builder. Module shape improved immediately with use of the feedback system, as the water collection area of the modules decreased by 55%. Later modules constructed by the operators were generally well-constructed, regardless of feedback system use, indicating a possible training effect. Since the total cost of the feedback system would be less than $500, farmers should see a rapid payback from improved module shape and lint quality.

Evaluating module shape was difficult, time-consuming, and inaccurate using existing techniques. A compressed biomass package measurement system was developed to record the heights of multiple points on the top surface of packages. The data collected was processed to calculate the sizes of depressions in these surfaces.

Repeated measurements on cotton modules indicated that height measurements by the system were accurate, with a measurement error of 5 cm (2 in.). The compressed biomass package measurement system was used for evaluating the powered tramper and autonomous module forming system.

A powered tramper was developed to move cotton from the sides of the module to the center. This system could be used alone, or with the feedback system. The powered tramper replaced the conventional tramper and operated automatically. The hydraulic circuit design still allowed full flow and pressure to the tramping cylinder. Cotton was conveyed to the center of the module using an auger with opposite-handed flighting.

Initial testing indicated that the powered tramper moved significant amounts of cotton to the center and produced crowned modules; however the measurement system was not available to use for evaluation. The primary method of moving cotton was for cotton to collect in the housing near the sides after a compression stroke. On the subsequent compression stroke, the cotton was conveyed out of the housing closer to the center of the module. The data collected with the module measurement system did not indicate an improvement in module shape with the powered tramper. However, the powered tramper was turned off prematurely due to an improperly sized valve on the module builder.

An autonomous module forming system was also developed that allowed modules to be built without an operator. The system utilized the sensors used for the feedback system and a commercial automatic tramping system. Additional photoelectric sensors were used to determine the level of cotton in the module builder. Algorithms were developed to efficiently move and compress cotton based on the sensor data.

The boll buggy operator controlled the autonomous system through a wireless display mounted in the boll buggy tractor cab. After unloading cotton, the operator would start the system. The autonomous system moved cotton towards the ends to create room for additional loads, compressed the final load of cotton, or quickly packed the cotton if the operator could only partially unload the boll buggy.

Modules built using the autonomous system were shaped more desirably than modules constructed by a human operator, with a 64% reduction in the water collection area along the length and a 25% decrease in the number of depressions. The operating time required to build a module averaged 37.4 minutes, comparable to an experienced human operator. Boll buggy operators found the wireless interface easy to use.

These systems provide a range of options for cotton producers. The feedback system is inexpensive, but does not eliminate any labor. However, use of the feedback system should result in module shapes that do not collect water and greater profits through cotton quality preservation. The autonomous system would cost more, but provide greater returns as labor is eliminated. The powered tramper could be used alone or in conjunction with the feedback or autonomous systems.

7.2. RECOMMENDATIONS

7.2.1. Feedback System

The ultrasonic sensor was accurate and generally reliable. However, the sensor currently used must be mounted in a housing. Problems were encountered during testing with water entering the housing and damaging the sensor circuitry. A more ruggedized version of the ultrasonic sensor should be used. Alternatively, reversing the location of the sensor and the target plate would provide a greater degree of environmental protection, although wiring would be more difficult.

The proximity sensors used to detect carriage motion only have an 8 mm maximum sensing distance. The carriage drive shaft has significant eccentricity in its motion due to its long unsupported length. The induced translational motion in the sensing hub makes adjustment of the proximity sensors difficult. The distance from the faces of the teeth on the sensing hub to the sensor face will vary from near zero to the maximum sensing distance of 8 mm. Mounting the sensors closer to a bearing would reduce the eccentricity. Alternatively, rotation of one of the sprockets could be sensed. In either case, proper shielding needs to be in place to prevent injury to an operator.

The algorithm for identifying tramping strokes should be improved. The delay introduced by calculating a moving average of the tramper values should be considered in calculating the distance the tramper moves. Reducing the tramper movement threshold should also increase the percentage of tramping strokes identified, without causing leveling actions to be recorded as tramping strokes. Modifying the outlier detection threshold should prevent the display of tramping strokes at incorrect heights.

7.2.2. Compressed Biomass Package Measurement System

Several modifications should improve the performance and durability of the system. The aluminum frame comprising the adjustable height mass was deformed slightly; however, no change in performance was noted. This deformation likely resulted from the sudden, oscillating loads that occurred as the vehicle was driven over rough terrain. Aluminum was originally used so that the system was lightweight and could be assembled by one person. An improved design may utilize telescoping steel pipe. Instead of attaching a rectangular steel frame to the parallel linkages, a single length of tubing would be sufficient to support the pipe. This design should not significantly increase the weight of the system.

This modified design would likely alleviate another issue with the system. The mast and arm were generally not completely horizontal due to the weight of the system and the movement allowed by the pinned joints of the parallel linkage. This deviation from horizontal was accounted for by the inclinometer mounted on the arm. Adding a third parallel linkage at a different vertical height would also reduce or eliminate this deviation from the horizontal.

The fingers should be replaced with a more rigid plastic and extended to 91.4 cm (36 in.) long. When disassembled for transport, the fingers were occasionally bent slightly. The fingers could be manually straightened; however, this process required time and likely contributed some to the measurement error. Using longer fingers would reduce the need to stop measuring and adjust the mast height, allowing measurements to be taken significantly faster.

To maximize the usefulness of this tool, the minimum depression size that can affect cotton quality needs to be quantified. One method of accomplishing this task would be to record heights and cover the modules. Immediately following a rain event during storage, the depressions holding water would be identified, and compared to the module height surfaces generated by the data analysis program. The insignificant smaller depressions should not collect water when covered, and a threshold for the minimum significant depression size could be established. This testing would also provide more data to quantify the performance of the system.

7.2.3. Powered Tramper

Additional data needs to be collected to evaluate the powered tramper with a properly functioning module builder. The hydraulic circuit needs to be modified to prevent failure of the motor shaft seal. The simplest option would be to use a motor with a high-pressure shaft seal. Another possibility would be to connect the motor between the tramping cylinder and reservoir, instead of between the cylinder and pump, resulting in much lower case pressures. This would require the use of a latching relay and an additional pressure switch to control operation.

The powered tramper could be modified to an entirely mechanical design. The hydraulic components add significant cost to the system and pose the risk of oil contaminating the cotton. A mechanical power transmission system would be implemented to use the linear motion of the tramper to power the rotary motion of the auger. A slip-clutch could be used to transmit power to the shaft, so the auger would stop turning when the torque required to rotate the auger increased above a desired setting. Alternatively, the current pressure switch could be used with an electric clutch.

7.2.4. Autonomous Module Forming System

Several modifications to the autonomous system should improve its reliability. Increased protection and better routing of the cable to the photoelectric sensors on the tramper should prevent breakage of this cable. A more ruggedized version of the ultrasonic sensor needs to be used. The current sensor functions well; however, the circuitry is not well protected from rain and dust.

The photoelectric sensors on the corners of the module builder had problems with misalignment and damage during transport. The rear sensor on the side used for unloading is likely to be damaged by the boll buggy when an operator backs up during unloading. As a result of these observed and potential problems, these sensors should be replaced with a mechanical sensor. These sensors would be mounted on the carriage and signal the control system when cotton is contacted.

The current boll buggy display is not suitable for use with the wireless communication system. A simpler display model, the DVC61, offered through High Country Tek should function satisfactorily with the wireless transceivers, and is less costly than the model used during testing. This text display module has 10 digital inputs that can be used for operator commands. Fewer bytes must be transmitted from the control module to the display, with an increased likelihood that messages are transmitted successfully.

The primary addition needed to the current system is the addition of a safety switch to prevent the module builder from starting while the boll buggy is unloading. A limit switch could be mounted on the module builder to sense when the boll buggy is raised to unload. This limit switch would be connected to the control system and prevent any carriage movement when actuated.

Another improvement needed for commercialization is the extension of the system to multiple boll buggies and module builders. The wireless transceivers will allow mesh networking; however, software modifications are required to establish communication protocols between the equipment. Since all machines in a network can receive messages from any machines, identification numbers must be assigned to each piece of equipment and transmitted with each message.

A typical communication sequence would begin with a boll buggy broadcasting a message to search for an available module builder. A module builder ready for additional cotton would respond with a ready message. The boll buggy would select a module builder based on some criteria, such as the first message received. Once communication is established between a pair of machines, messages from other equipment would be ignored until the cotton is unloaded.

The algorithms used for the movement and compression of cotton could be modified to decrease the time required to build a module or build modules with more desirable shapes. During some passes, the second set of actions to move cotton to the ends were likely unnecessary. Improved criteria for determining whether to perform this step would result in a faster module building algorithm. An improved finishing algorithm could result in more desirable module shapes, regardless of user actions. Cotton could potentially be moved from high regions to low regions, resulting in a crowned shape. Diagnostic capabilities and increased fault tolerance could also be incorporated in the software.

7.2.5. Additional Applications

Significant research has recently focused on the production and processing of crops for energy. A primary challenge in producing biomass for energy is the logistics of storing and transporting large quantities of material (Biomass Research and Development Technical Advisory Committee, 2007). The logistics of handling cotton have been studied by researchers as a model for handling biomass (Ravula et al., 2008). Module builders have been used to compress materials other than cotton. Mueller et al. (1995) demonstrated the feasibility of using a module builder to compress alfalfa for storage.

Systems for handling biomass will likely require packaging the material at an increased density. Furthermore, these packages may need to be stored for long periods of time. While harvesting periods are seasonal, energy generation is necessary year-round. Consequently, maintaining the quality of stored biomass will be an important aspect of the economic feasibility of these systems. The feedback system and powered tramper technologies may be applied to biomass storage techniques to preserve the quality of biomass. Concepts of the autonomous module forming system may also be applied to biomass handling systems to reduce labor requirements. The measurement system should be useful in evaluating the effects of different biomass storage techniques.

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APPENDIX A

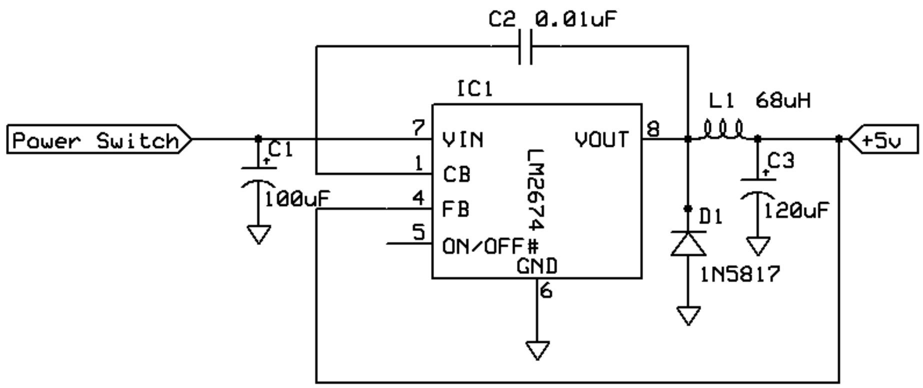

Figure A.1. Feedback system 5 V regulator schematic.

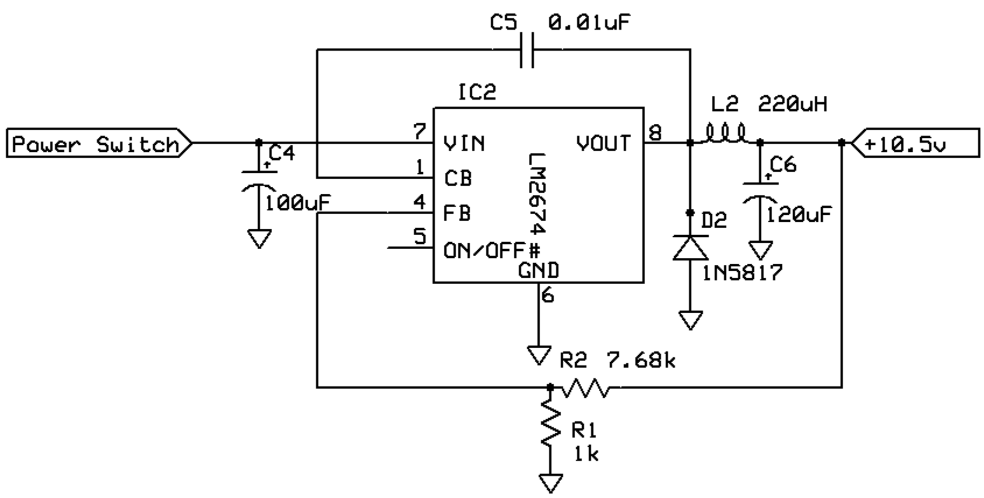

Figure A.2. Feedback system 10.5 V regulator schematic.

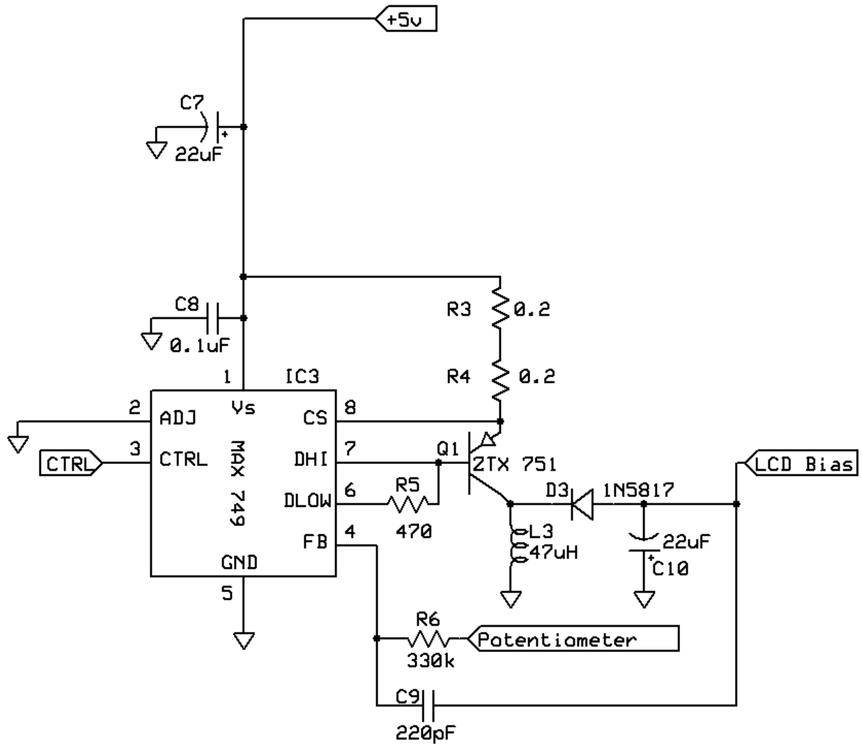

Figure A.3. Feedback system LCD bias voltage schematic.

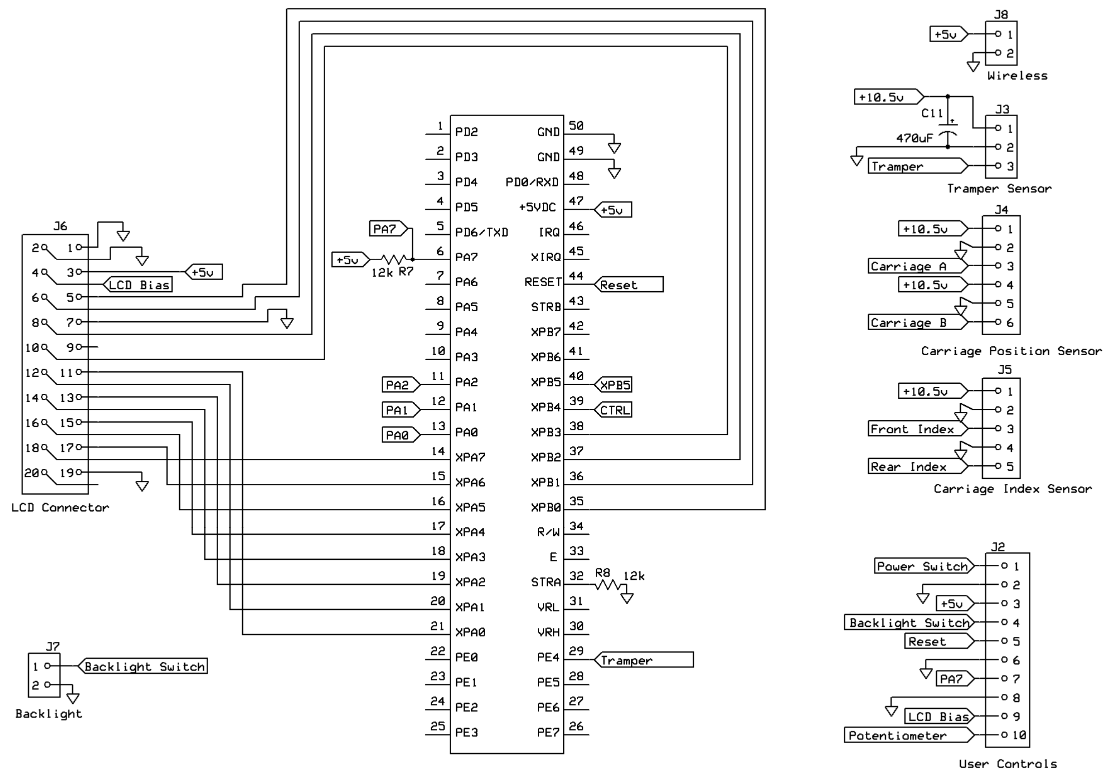

Figure A.4. Feedback system control and sensing schematic.

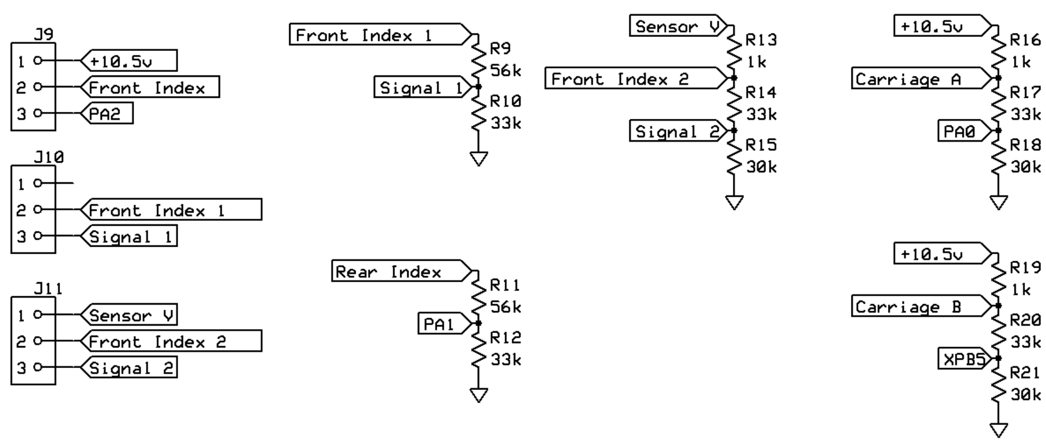

Figure A.5. Feedback system proximity sensors schematic.

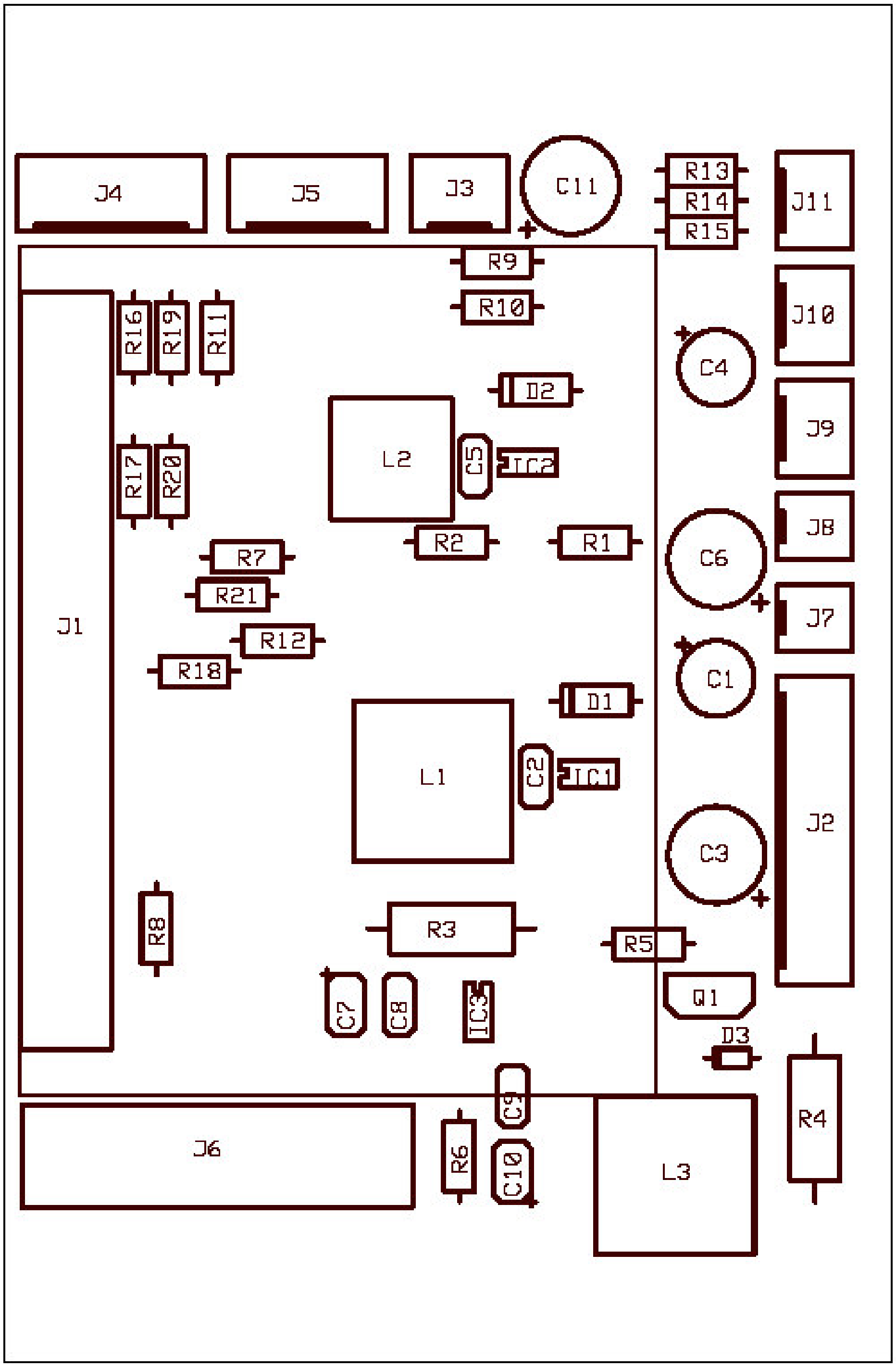

Figure A.6. Feedback system circuit board component layout (enlarged for readability).

Table A.1. Feedback system circuit components.

ID	Component	ID	Component
C1	100 μF	J11	Connect to J9 for Big 12
C2	0.01 μF	L1	68 μH
C3	120 μF	L2	220 μH
C4	100 μF	L3	47 μH
C5	0.01 μF	Q1	ZTX751
C6	120 μF	R1	1 kΩ, 1%
C7	22 μF	R2	7.68 kΩ, 1%
C8	0.1 μF	R3	0.2 Ω
C9	220 pF	R4	0.2 Ω
C10	22 μF	R5	470 Ω
C11	470 μF	R6	330 kΩ
D1	1N5817	R7	12 kΩ
D2	1N5817	R8	12 kΩ
D3	1N5817	R9	56 kΩ
IC1	LM2674	R10	33 kΩ
IC2	LM2674	R11	56 kΩ
IC3	MAX749	R12	33 kΩ
J1	Microcontroller Board	R13	1 kΩ
J2	User Controls	R14	33 kΩ
J3	Tramper Sensor	R15	30 kΩ
J4	Carriage Position Sensor	R16	1 kΩ
J5	Carriage Index Sensor	R17	33 kΩ
J6	LCD Connector	R18	30 kΩ
J7	Backlight	R19	1 kΩ
J8	Wireless	R20	33 kΩ
J9	Module Builder Select	R21	30 kΩ
J10	Connect to J9 for Crustbuster		

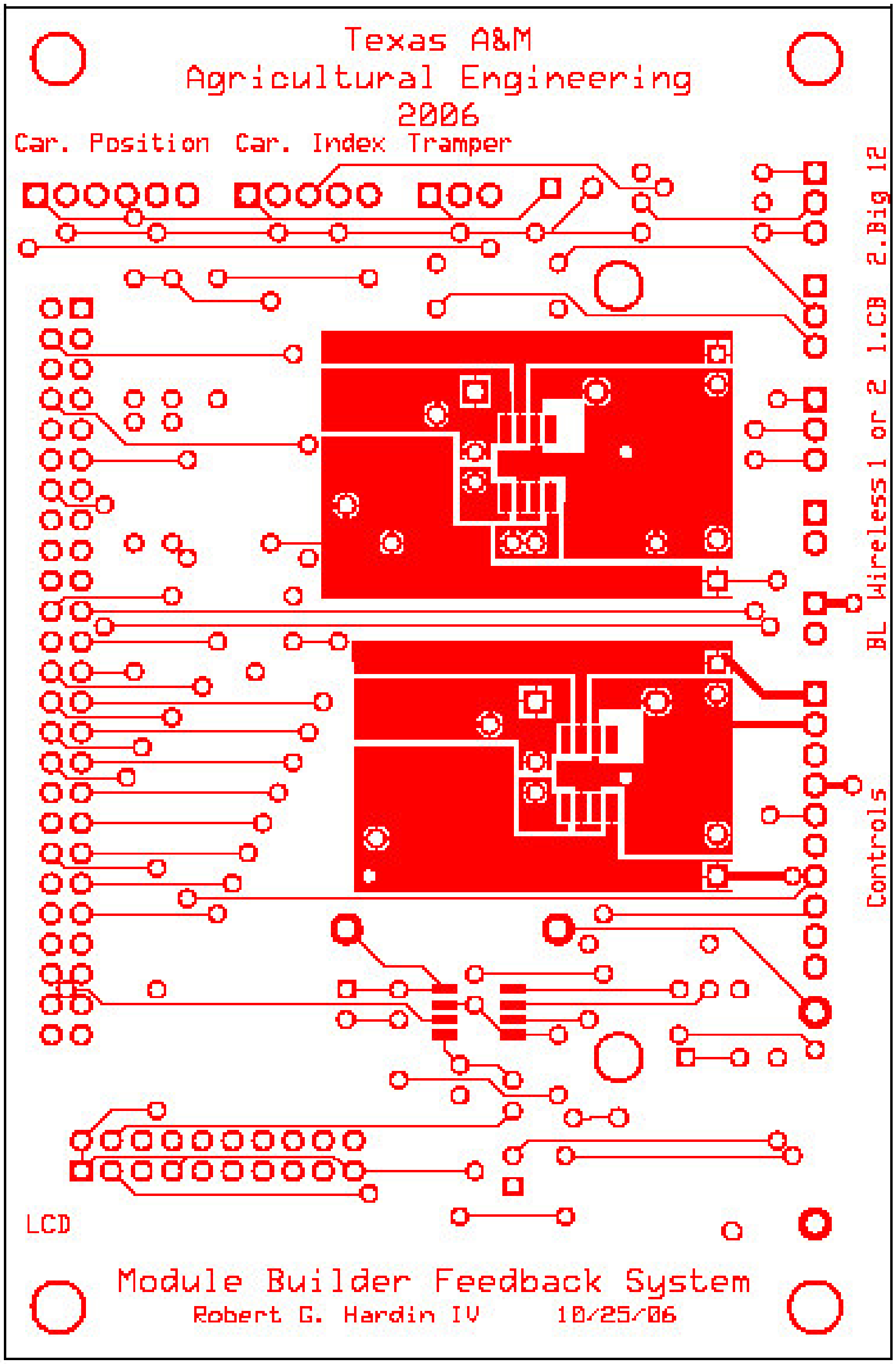

Figure A.7. Feedback system circuit board top copper layer.

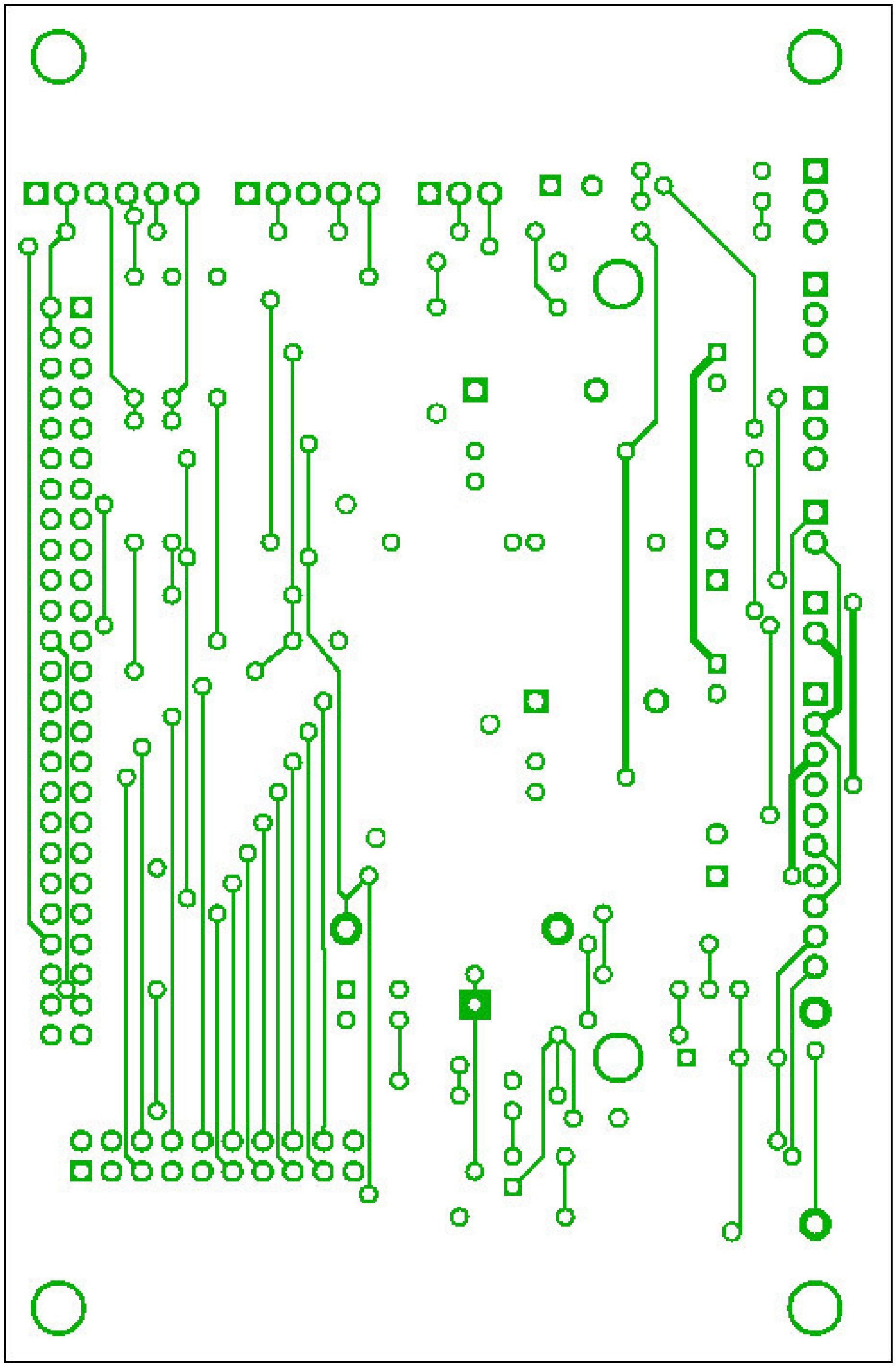

Figure A.8. Feedback system circuit board bottom copper layer.

APPENDIX B

SOFTWARE

B.1. FEEDBACK SYSTEM

The feedback system program was created in C for the 68HC11 microcontroller. The following programs are needed to implement the feedback system:

- mmv3_41.c: main program
- adapt11.h: register address for the Adapt11 evaluation board
- delay2.c: time delay function
- lcd.c: functions for using the graphic LCD screen
- sci.c: serial communications functions
- bias2.c: functions for controlling LCD bias voltage
- adc.c: analog to digital converter functions
- mm_lcd.c: functions for LCD specific to feedback system program

The program requires that the microcontroller timer prescaler be set to 16. This action is done by setting the two least significant bits in the timer mask register 2 (TMSK2 = 0x03). This code must be executed during the first 64 bus cycles after reset. Implementation of this code depends on the C compiler used, but may involve modification of library files.

Data collected from the feedback system was initially converted from binary to comma separated variable files using a visual basic program. A Microsoft Excel macro was used for further analysis:

- Binary to CSV Converter: Executable file
- Binary to CSV Converter (folder): Contains files for visual basic program
- Feedback System Data Processor.xls: Excel macro

B.2. COMPRESSED BIOMASS PACKAGE MEASUREMENT SYSTEM

A Campbell Scientific 21x datalogger was used to record sensor data. The datalogging program was created in ShortCut, the Campbell Scientific programming application. Datalogger files were saved as *.csv files and initially processed in Microsoft Excel. Further processing was done in Matlab. The following programs were used:

- ModuleHeight.scw: ShortCut program, also produces wiring diagram
- ModuleHeight.bas: Visual Basic macro for Excel, used where zero position data was collected in field by rotating encoder in reverse
- ModuleHeightNoZeroData.bas: Visual Basic macro for Excel, used where zero position data on sensor position was not collected in field
- IdentifyDepressions.m: Matlab program to characterize depressions in height surfaces, calls importfile.m and DepressionVolume.m. Allows user to select multiple input files and outputs 3 files per input file (* is name of input file):
    - *_1.mat: for each depression, lists volume, depth, and surface area

    - *_2.mat: contains summary statistics for each surface- total depression volume, number of depressions, average depression depth, maximum depression depth, and average surface area
    - *.fig: height surface with depressions
- importfile.m: Code to import an Excel file into Matlab
- DepressionVolume.m: Code for producing height surfaces and characterizing depressions
- LengthWidthProfiles.m: Matlab program that calculates water collection areas in the average length and width profiles of a height surface, calls importfile.m and AverageModuleSlice.m. Allows users to select multiple input files and outputs 5 files per input file (* is name of input file):
    - *_a.mat: average heights for each position along the length of the surface
    - *_b.mat: average heights for each position along the width of the surface
    - *_c.mat: potential water collection areas for the average length and width profiles
    - *lg.fig: plot of average height and potential water collection areas along the length of the surface
    - *wd.fig: plot of average height and potential water collection areas across the width of the surface
- AverageModuleSlice.m: Code for generating average height and width surfaces and calculating potential water collection areas

- WaterAreaWidthSlices.m: Calculates the potential water collection areas of multiple cross-sections across the width of a package, calls ModuleHeight.m. Used for evaluation of the powered tramper. Allows users to input multiple files, outputs one array containing the water collection areas for each slice and an identification field corresponding to the input file.
- ModuleHeight.m: Code for calculating the water collection areas of multiple cross-sections across the width of a package
- statsmatrix.m: Combines the statistical parameters contained in the *_2.mat and *_c.mat files described above for multiple measurements. Also allows the user to input codes for treatments in a statistical analysis. Outputs one file for statistical analysis.

B.3. AUTONOMOUS MODULE FORMING SYSTEM

The program was developed using the Intella software for the High Country Tek DVC hardware. A pdf file is included with text of the program code.

- AMFS.dvc
- AMFS.pdf

B.4. FILE LOCATION

All files are located on CD. To obtain copies, please contact:

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Hardin IV, R.G. and S.W. Searcy. 2008. Viscoelastic properties of seed cotton. *Trans. ASABE* 51(3):803-810.