CAPSTONE DESIGN EXPERIENCES IN THE DEVELOPMENT OF A TWO-ROW PLOT SCALE POTATO PLANTER

D. D. Steele, T. A. Bon, J. A. Moos

ABSTRACT. *Practical experience in the design process is an important part of undergraduate engineering education. The objective of this article is to illustrate how an ongoing research project provided design opportunities for undergraduate engineering students. Student teams in a capstone design course were engaged in the redesign and rebuilding of a mechanical plot-scale, two-row potato planter capable of planting in both the conventional hill (ridge) mode and in a furrow (trench) mode as part of a research project comparing planting configurations. Students used engineering design tools such as decision matrices, engineering standards, failure mode and effects analysis, three-dimensional parametric modeling of design alternatives, finite element analyses of stress and strain, and laser cutting of parts by a local manufacturing company. The first team of students redesigned and rebuilt the potato planter in one semester. Their accomplishments included redesigning the disk opening system and moving the ground drive/depth control wheels ahead of the disk opening system. The modified planter was used for two years of field plot research and additional design needs were identified. Feedback from the first design was used as input for a second student team to work through a similar redesign and rebuild cycle. The second team of students redesigned and rebuilt the disk closing system and shortened the overall length of the planter during a two-semester capstone course. Both versions of the planter were used successfully in the field for small plot experiments. Concepts and designs from this project can be used as the basis for additional research, student instruction, and commercial applications. Suggestions for improvement of instruction and improvement of the planter are given and safety issues are noted.*

Keywords. *Education, Computer aided design, Machine design, Machinery, Potatoes, Planters, Inter-row water harvesting.*

Criteria for the Accreditation Board for Engineering and Technology have moved toward a "closing the loop" or feedback and adjustment approach (ABET Inc., 2007) in which education includes constituents both outside the classroom and student constituents inside the class. This article covers the recognition of modifications needed for a two-row potato planter during a multi-year research project and subsequent engagement of teams of undergraduate engineering capstone design students to redesign and rebuild the planter for plot-scale field use. After the first capstone design team completed their modifications, the modified planter was evaluated under actual research plot conditions and conclusions were drawn. This evaluation led to a refined set of desired improvements and modifications which was then presented to a later capstone design team. The second team participated in another cycle of the design process, from conceptualization to design to rebuilding of the planter, and additional conclusions were drawn.

The objective of this article is to illustrate how the ongoing research project on potato planting configurations provided design opportunities for undergraduate engineering students. We present the planter used by Steele et al. (2006), describe the need and design constraints for a plot-scale potato planter capable of planting in both hill and furrow configurations, chronicle the redesign and modifications made to an existing planter by teams of undergraduate engineering students, report the results achieved and improvements made over multiple seasons of field use, suggest areas for improvement, and note safety considerations.

PRELIMINARY DESIGN CYCLES

Replicated field plot studies designed to compare potato planting configurations require that seedbed geometry, row spacing, seed spacing in the row, planting depth, fertilizer application rates and placement locations, and chemical application rates be held constant for each experimental treatment. Specialized seedbed geometries and precise control of the aforementioned planting variables can be achieved by manual operations, but mechanization is necessary when the area per plot, the number of treatments, or the number of replications increase. For example, Steele et al. (2006) required a machine to plant 32 plots, each four rows 3.6 m (12 ft) wide by 12.2 m (40 ft) long, in each year of a three-year study to compare row orientation and furrow versus hill planting configurations for potatoes.

Commercial potato planters such as Harriston (Harriston/Mayo, Minto, N.D.) or Lockwood (TerraMarc Industries,

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West Fargo, N.D.) are typically built in four-, six-, or eight-row units. Two-row units are available from some manufacturers. Most commercial planters are designed for hill or ridge planting only, but some growers are planting into existing beds, such as using a 43-cm (17-in.) row spacing with four or five rows per bed, or planting into pre-marked rows (D. Dunnigan, 2005 personal communication, Harriston Company, Minto, N.D.). Typical research studies employ two-row planters to facilitate small plot sizes; accommodate frequent changes in cultivars, fertility levels, and other variables; provide greater control and precision in planting operations; and keep costs down.

Mechanical potato planters for plot-scale research have been described by Misener and McLeod (1988) and Arsenault et al. (1996). Misener and McLeod did not discuss seedbed geometry such as hill or flat planting, but emphasized the capability of their planter to control variables such as in-row seed spacing, row spacing, and fertilizer placement. They tested the accuracy of their planter's seed placement as indicated by the coefficient of variation (CV) for seed spacing. Arsenault et al. (1996) reported similar design features on their planter and reported lower CVs for seed spacing than Misener and McLeod (1988). The Arsenault et al. planter was a flat planter with hill formation conducted as a separate operation after planting.

To design a potato planter for operation in both hill and furrow planting modes, the following design considerations and operating constraints were used: complete interchangeability between conventional (hill or ridge) planting mode and furrow planting mode in a timely fashion, minimal soil disturbance and compaction after formation of hills or furrows, adjustable seed spacing and depth capabilities, separate liquid fertilizer and liquid insecticide application capabilities, and operator safety. We do not address statistical comparisons of performance measures, such as CVs of seed spacing, for the machine developed herein with that of any other planter. We also do not address design criteria for large-scale production, such as detailed stress and strain analyses, material optimization, benefit-cost analyses, etc. because the machines depicted were intended as one-of-a-kind machine for research purposes only.

The planter described herein was used for small plot field studies in North Dakota to compare row orientation and hill versus furrow planting configurations for potatoes (Steele et al., 2006). Potatoes for all plots and years were planted with a 0.91-m (36-in.) row spacing with 0.30-m (12-in) seed spacing in the row. Plots were four rows wide by 12.2 m (40 ft) long. Soil descriptions are provided in the context of the yearly test plot locations which follow. The tractor and implement ground speeds in the studies reported here were typically 0.31 to 0.45 m s^{-1} (1.0 to 1.5 ft s^{-1} or 0.7 to 1.0 mile h^{-1}). This speed range is considerably slower than commercial planting units [e.g., 2.9 m s^{-1} (6.5 mile h^{-1}) (Fairbourn, 2007)], but is necessary because seed placement is done by hand, not by machine.

Work in 2000 focused on development of the furrow versus hill planting concept and did not involve a student design team. A preliminary trial comparing hill, bed, and furrow planting configurations for potatoes involved three different tractor-mounted implements. Hill planting was accomplished using a conventional two-row planter equipped with an opening shoe; seed piece hopper and delivery mechanisms; insecticide tank, hoses, nozzles, etc.; and closing disks. Bed formation was accomplished by an implement used to form raised beds for carrot production. Furrow formation was accomplished with a toolbar used to install subsurface drip irrigation tape (Steele et al., 1996). The furrow-forming toolbar was modified to hold four 0.41-m (16-in.) diameter concave disk openers to create a V-shaped furrow (fig. 1). The disk openers were identical to those used on Lockwood potato planters (Crary/TerraMarc Industries, West Fargo, N.D.). After seedbed formation for both the bed and the furrow configurations, holes for seed pieces were dug with a hand shovel, seed was placed by hand, insecticide was applied using a portable, hand-operated spray unit, and the seed pieces were manually covered with soil. Usage of three different machines and manual planting was labor and equipment intensive. The 2000 trials were located on a Maddock sandy loam (sandy, mixed, frigid Entic Hapludoll) at the Oakes site.

The modified subsurface drip irrigation plow formed sharp V-shaped furrows (fig. 2) for the furrow planting trial.

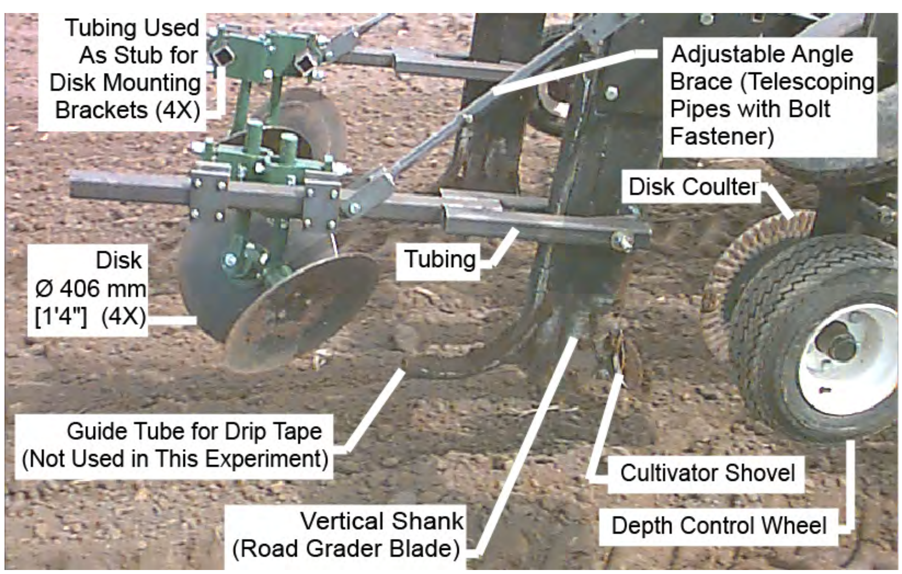

Figure 1. Side view of toolbar designed for installation of subsurface drip irrigation tape. The disk openers were added in 2000 for furrow formation.

Figure 2. Furrow formation in progress with the modified subsurface drip irrigation plow in 2000.

Advantages of this approach included relatively low cost and easy implementation. Disadvantages of this approach included the requirement of manual operations for virtually all tasks after furrow formation, including hand measuring, marking, and digging of holes for seed pieces, manual spraying of insecticide, manual seed piece placement, and manual coverage of seed pieces. In order to make statistical comparisons of treatment means, replication of plots was recognized as necessary (Montgomery, 1997) and a potato planter with hill-furrow interchangeability was needed.

Work in 2001 focused on the addition of basic furrow planting capabilities to a two-row plot scale planter and did not involve a student design team. We obtained access to a custom-built two-row planter (fig. 3) which served as the base unit for subsequent design modifications. The unit was patterned after Iron Age models (Batemann Mfg. Co., Greenloch, N.J.; Wendel, 2005), was designed for mini-tuber unit planting (D. Preston, 2005, personal correspondence), planted in a hill configuration, and was mounted on a three-point hitch of a tractor. The operator for each row places seed pieces on one of two 0.75-m (29.5-in.) diameter rotating aluminum carousels with 18 holes around the perimeter. Both carousels are driven from the right wheel through a system of sprockets, chains, and gears. A table under the carousels supports the seed until each piece falls into the drop tube for each row. The carousel is significantly larger in diameter and holds more seed pieces compared with commercial units for plot-scale work. The larger diameter produces a slower angular velocity, allowing more time for operators to see and correct skips or doubles in seed piece placement and allowing more time for switching seed types. The shoe-type opener in front is similar to those used on Lockwood planters. Modifications to the planter in 2001 were made in the North Dakota State University (NDSU) Agricultural and Biosystems Engineering (ABEN) Department's shop with no engineering student involvement.

We recognized a safety hazard in the planter because the rotating carousel with its seed holes rested directly on the table beneath it. A finger could have been sheared off as the seed holes in the carousel rotated over the stationary drop tube. A small guard or covering shield was present over the drop tube location but this was not deemed sufficient to prevent injuries; in fact it could have increased the chances of entanglement. To address this safety concern, the carousel was raised 11 cm (4.5 in.) above the table (fig. 4) and the

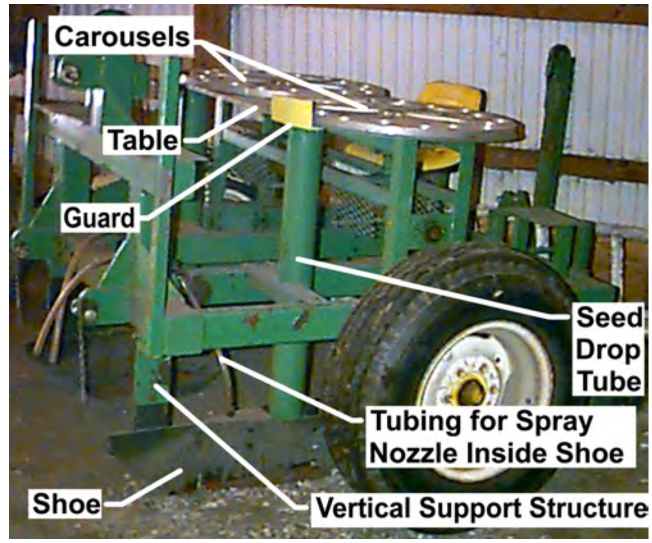

Figure 3. Custom-built two-row planter for mini-tuber unit planting (near operator seat is missing).

covering shield removed. An extension drop tube was constructed for each hole and consisted of steel conduit 7 cm (2.75 in.) in diameter and 5.1 cm (2 in.) long and inserted in the holes in the carousel. Each conduit piece was connected to a section of water discharge hose 10.8 cm (4.25 in.) long which was held in place with a hose clamp. The water discharge hose had a 10-bar (150-psi) rating and therefore was rigid enough to move seed pieces along the table yet flexible enough to prevent hand injuries, finger entrapment, etc. If two seed pieces were accidentally dropped into an extension drop tube, they were either left "as is" or one was quickly skewered from the top with a long screwdriver and discarded. The seed retrieval options were recognized as not ideal but were preferred over the safety hazard.

Disk openers were mounted on the front of the planter to enable furrow planting. The original planter had a vertical support structure (fig. 3) for each row consisting of 13-mm (0.5-in.) flat steel welded between the 102- × 102- × 4.8-mm (4- × 4- × 3/16-in.) main front frame member and the top of the shoe. A horizontal mounting structure (fig. 4), also made from 13-mm thick plate steel and approximately 305 mm (12 in.) long and 102 mm (4 in.) high, was bolted to the vertical support structure and used to mount the disk hardware for each row. No engineering design analysis was done when choosing the 13-mm (0.5-in.) steel plate or the 51-mm (2.0-in.) square tubing for mounting the disk opening hardware. (A failure is discussed later.) The 13-mm (0.5-in.) steel plate was material available in our shop. The square tubing was required to mount the clamping system of the factory built (TerraMarc) disk hardware and the tubing was on hand.

In the furrow planting mode, the rear disk closers were raised to lightly cover the tubers with soil. For hill planting, the front disk openers were removed and the planter was used in its normal mode. The disk closing system did not produce as much mounding of the soil into a hill as desired for the hill planting mode, but soil coverage over the seed pieces (reported by Steele et al., 2006) was considered adequate.

At the Oakes site, the Maddock soil was somewhat moist and tended to stick to the tires and thereby increase the tire diameter. Because the carousel was ground driven, the larger

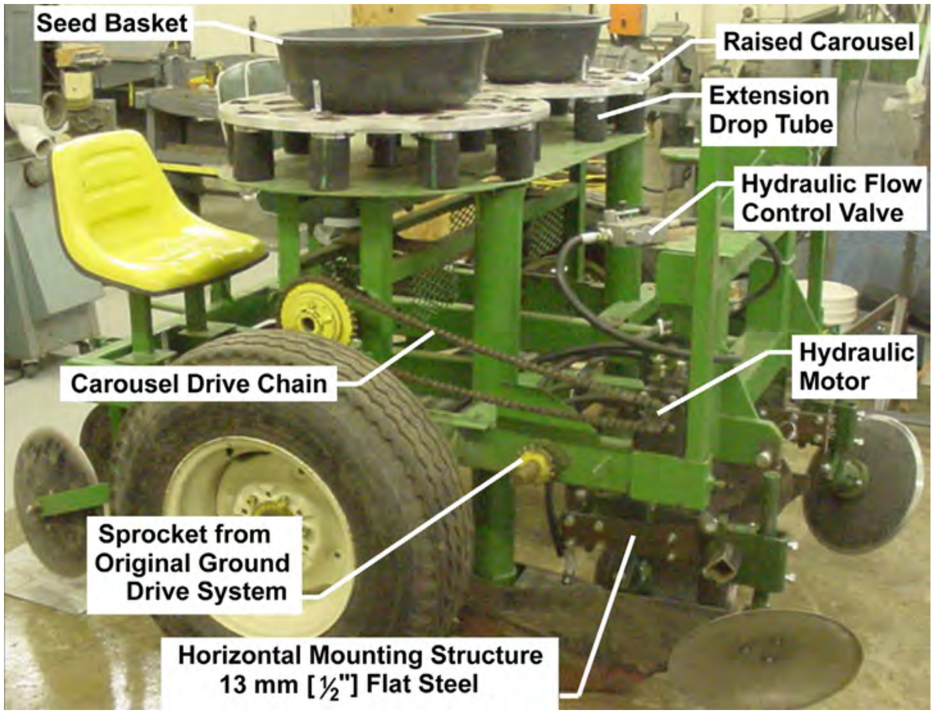

Figure 4. Modified potato planter used in 2001. Shields have been removed to show details.

tire diameter increased the in-row seed spacing if operators were not careful to keep the tire clean. The soil adhesion problem was more pronounced in the furrow planting mode because the disk openers in the front exposed moist subsoil that was subsequently tracked due to the rearward placement of the drive wheels. The tires also had the undesirable effect of compacting the midrow ridge for the furrow planting mode. Compaction of the midrow ridge was considered undesirable because of its potential to reduce the inter-row water harvesting effect. In the hill planting mode, the tires traveled in line with the tractor tires, i.e., over undisturbed soil, and had negligible soil adhesion.

To overcome the soil adhesion problem, we removed the ground drive wheels and used a hydraulic motor to drive the carousel (fig. 4). The hydraulic motor used to drive the carousel was obtained from our department's hydraulics instruction lab. The motor was tested to be sure it met the project's speed requirements before mounting on the planter. At the Dawson site, the appropriate in-row seed spacing was achieved by determining an appropriate tractor throttle setting to achieve the desired ground velocity with the planter unit engaged in the soil, then adjusting the flow control valve in the hydraulic line so the angular velocity of the carousel would produce the correct seed drop rate. Some departure or drift in the flow control valve setting was observed, so we had to recalibrate the angular velocity for each replication of the study to ensure uniform seed spacing. A computer-controlled seed spacing system was not considered because of time constraints during the brief window of optimal planting time. A seed spacing control system could be designed using sensors to measure ground speed and to detect seed piece motion (count and timing) in the drop tubes, a controller, and a variable-speed motor or other adjustment for carousel speed.

The disk opening system on one side of the planter yielded during planting operations at Dawson. The failure consisted of a bend of approximately 19° in the vertical mounting structure immediately below a triangular reinforcing flange. The bending was attributed to excessive stress induced by the loading on the disk openers and apparently occurred gradually over the course of planting operations at Dawson. The bending was not observed as a single event at one instance of, for example, lowering the planter into the soil. Plots at the Dawson site were located on Towner loamy fine sand (sandy over loamy, mixed, superactive, frigid Calcic Hapludoll).

We recognized the need for a ground-driven carousel with the drive wheels located in front of the front disk openers and the need for an improved mounting system for the front disk openers. A ground drive system would prevent the need for calibration and adjustment of a hydraulic system. The front position of the ground drive wheels would minimize soil adhesion on the tires and would minimize compaction of the midrow ridge when operating in the furrow planting mode. A stronger mounting system was needed to prevent yielding.

First Design Cycle with Student Involvement

The NDSU ABEN capstone design experience for undergraduate students is a two semester course sequence, ABEN 486, Design Project I, and ABEN 487, Design Project II. Objectives for ABEN 486 and 487 are: 1) to design a system, component, or process to meet desired needs in an agricultural system, biomaterials system, or environmental system problem incorporating necessary engineering, biological, and/or biosystems information; 2) to use techniques, skills, and modern engineering tools necessary for engineering practice to accomplish the first objective; 3) to develop written, oral, and graphical methods necessary to communicate [their] work to appropriate audiences; 4) to consider the social, environmental, and safety factors (as appropriate) in the design; 5) to work in a team setting to accomplish a capstone design project; and 6) any other factors necessary for the successful completion of ABEN 486 and ABEN 487 (Bon, 2006a and b). When possible, students develop a model or prototype and test it. The course objectives are consistent with the NDSU ABEN engineering program educational outcomes required by the Accreditation Board for Engineering and Technology.

Previous to the potato planter development projects described here, other capstone design projects involved university faculty as either the principal cooperator or one of the cooperators. Some examples include a multi-year mechanical broccoli harvester (Mahawold and Seibel, 1994; Paulson, 1995; Moger and Pietsch, 1996; Stoltman, 1997; Cuypers et al., 1998), an NDSU cattle research housing facility (Berg et al., 1999; Harmsen, 2000), and a flaxseed dehuller project (Runicki et al., 2001; Osowski and Hager, 2002). The mechanical broccoli harvester project involved prototype machines in all its iterations from 1995 through 1998. Based on observations of past projects, there was a good level of confidence the experimental potato planter project could also be successfully completed.

Work in 2002 focused on redesign of the planter used in 2001 and a capstone design team was enlisted to address some of the concerns found during the 2001 season. The team's objectives were to: 1) develop an accurate seeding rate/spacing to replace the existing hydraulic motor drive unit; 2) allow variable planting depth; 3) redesign the structural frame system supporting the shoe/disk mounts; 4) address operator comfort and ergonomics; and 5) meet time and cost constraints (Rockeman et al., 2002). The capstone design experience is intended to be completed during two semesters. However, on occasion students take the two courses in one semester, often due to students missing a semester due to cooperative educational (internship) engagements. During spring semester 2002, three students were in this situation and the potato planter modification project was proposed to them. The project met all the desired objectives for ABEN 486 and ABEN 487. This project allowed a "hands-on" application with a machine that would use the design modifications the student team proposed and require them to construct a working prototype. In addition, there were deadlines incorporated into the project because the prototype was to be operational in time for field use that spring.

Rockeman et al. (2002) made significant modifications in the planter. They developed a ground drive using sprockets and chains to replace the hydraulic motor drive unit. Wheel assemblies were designed to position the ground drive wheels in front of the disk openers to avoid compaction of the midrow ridge (fig. 5). The carousel was powered by a chain linked to the right ground drive wheel. Depth adjustment links for the ground drive wheels enable planting at different depths. Furrower structures were designed to hold disk mounting brackets at several user-selectable positions (fig. 6). The front ends of the furrower structures were designed to hold mounting brackets for furrowing shanks equipped with cultivator shovels (fig. 7). The cultivator shovels open the soil prior to its contact with the disks, thereby decreasing the stress on the disk mounting brackets. The carousel was moved rearward and the overall length of the planter increased. Ergonomics of the operators' seating area was improved. The project, including construction, was completed before the end of the semester and was under the allowed budget of $1000. Weather conditions in the spring of 2002 did not allow the team to test their prototype during the semester.

Rockeman et al. (2002) used engineering design tools to develop their solution. Decision matrices were used to

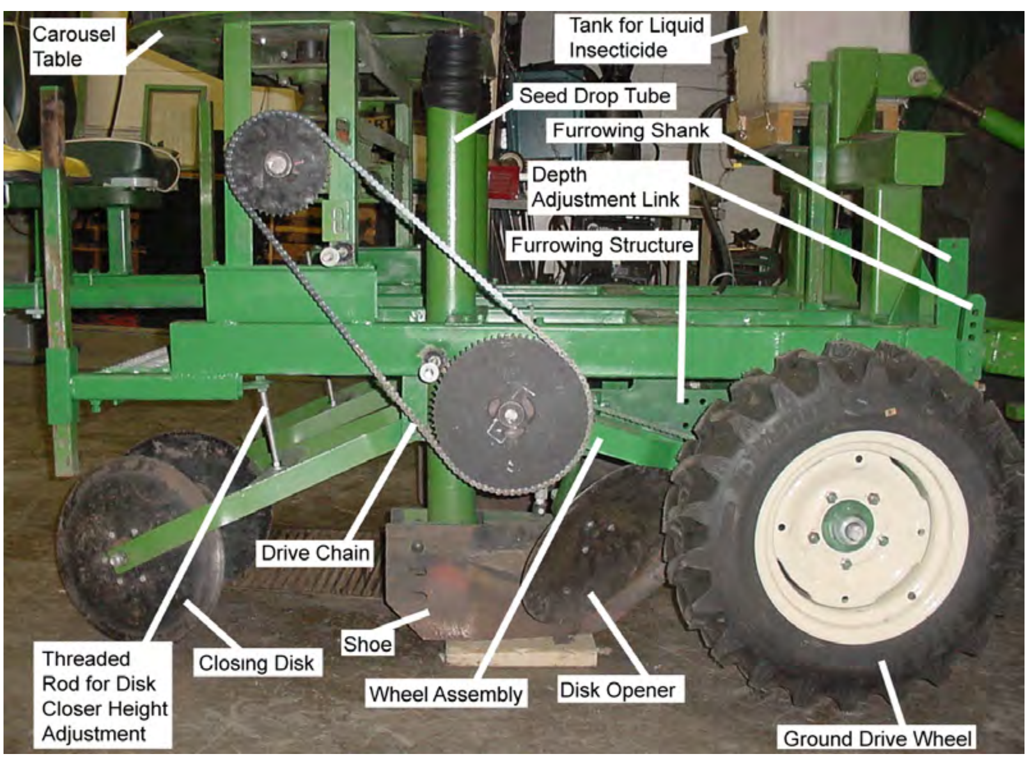

Figure 5. Potato planter after redesign in 2002 (gear and chain shield removed to show details). Travel direction is to the right.

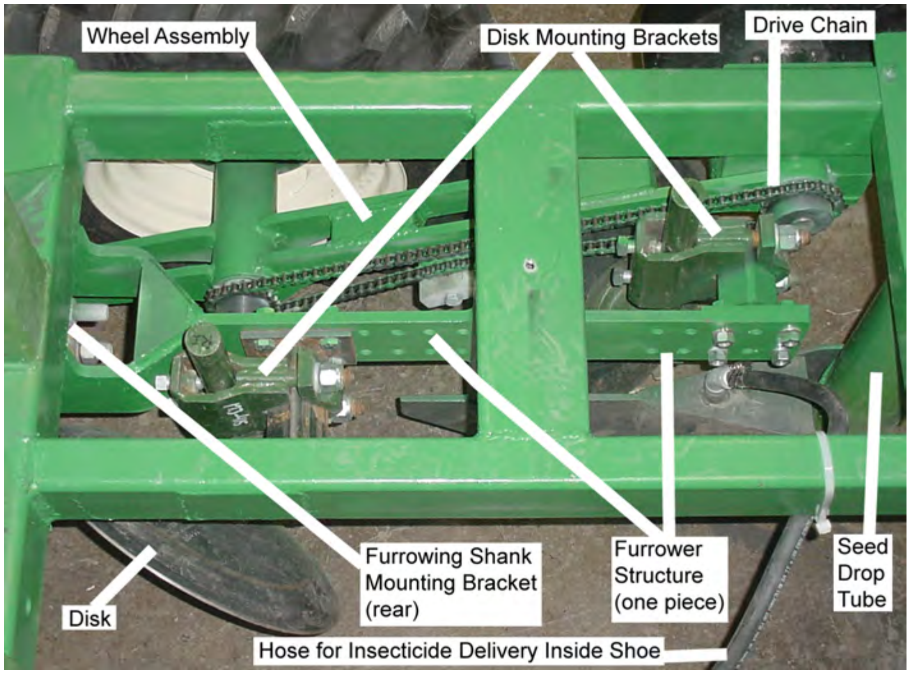

Figure 6. Furrower structure detail. Travel direction is to the left. This view is from the center of the machine looking toward the right side.

compare furrowing systems and closing systems. They did not redesign the closing system because of time constraints. Alternatives for the furrow opening system included structural modification of the system developed in 2001, two variations of a spider gang system, a redesigned disk assembly with and without a furrowing shank, and a moldboard assembly. Factors considered in the decision matrix included cost, interchangeability between furrow and hill planting modes, adequate seed piece coverage and ability to control soil movement, size, and compatibility with the existing structure, and ease of modification or future enhancement of the overall system. *Pro-Engineer* software (Parametric Technology Corp., 2000) was used to develop alternative designs for the potato planter. A constraint on the design was to keep the overall weight of the planter less than the minimum lift capacity for a three-point hitch on a 52.2-kW (70-hp) tractor (*ASABE Standards,* 2007b). The parts designed in *Pro-Engineer* were subjected to finite element analysis of stresses and strains (ANSYS Inc., 2001) expected for the structural members of the planter. Estimates of the expected loading were determined by modeling the machine and operator masses using *Pro-Engineer* and the soil force needed to cause the bending of the vertical support structure noted previously (Roark, 1954; Kepner et al., 1972;

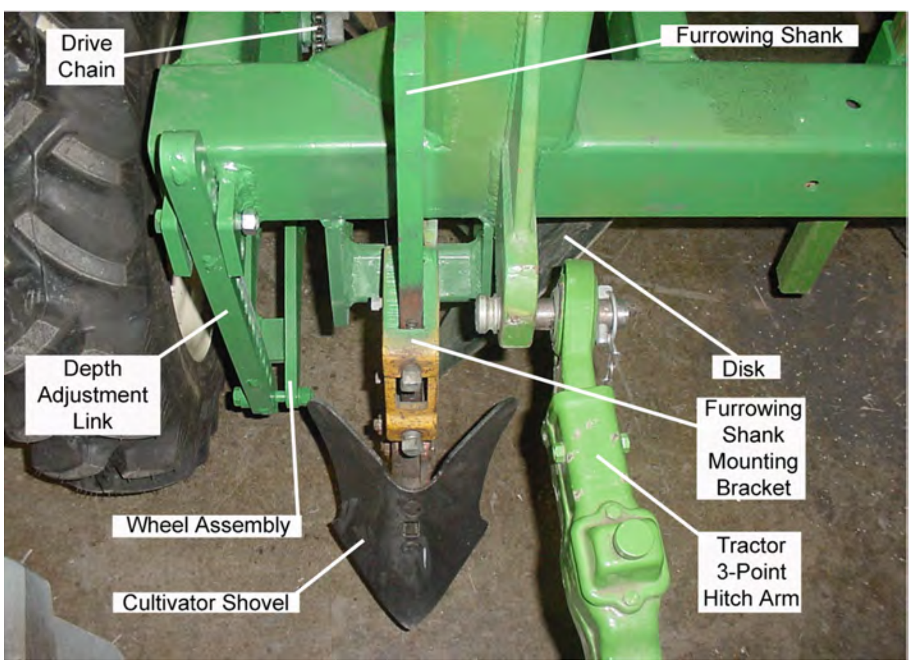

Figure 7. Front view of furrower structure and mounting bracket for cultivator shovel.

Hibbeler, 1997). [A later student team recognized that a more robust approach would be to use machinery management data (*ASAE Standards,* 1997) to estimate implement draft forces and forces on the disks.] Failure mode and effects analysis (Chrysler et al., 1995) was performed for the wheel assembly and the seat assembly and operator support. Potential failure modes included failures in welds, materials, and hardware. Some parts used for the 2002 modification of the planter were laser cut by a local manufacturing company using the *Pro-Engineer* models developed by the student team. The parts were cut from 13-mm (0.5-in) A36 steel or steel with higher yield strength to simplify manufacturing. Different thicknesses may have been more appropriate for production runs to minimize cost and weight, but we note that the cutting was a donated service, uniform thicknesses would avoid confusion, and we preferred overdesign for our research project to avoid the risk of downtime and lost plot years that could have been caused by part or material failures. The 13-mm (0.5-in) steel was found to have adequate strength based on the finite element analyses performed. The team presented their design in an oral presentation near the end of the semester and documented their work with a written report (Rockeman et al., 2002).

Design of a system for electronic control of seed spacing was not considered a viable option by the student team for several reasons. The project was to be completed in one semester, thus forcing the design team to concentrate on structural redesign and fabrication rather than selection, purchase, installation, testing, and debugging of sensors, controllers, and software. The budget was very limited and would not have allowed purchase of the necessary items. We required a reliable and functioning seed delivery system for use in the field research projects and the ground drive system met this objective. Fluid power systems would be the most likely system to be interfaced with the instrumentation and controls for feedback control system, making a much more complex design in the limited time. The team did not have a strong background in instrumentation and control systems.

Life-cycle or other repetitive testing was beyond the scope and time constraints of this project. Note that the students were designing for a research project in which some overdesign was acceptable; they were not designing for mass production in which life-cycle and other controlled and repetitive testing, re-analysis, and redesign for cost and weight savings would be expected. Nonetheless, the planter was subjected to numerous operational cycles in the course of field research after each design cycle. For the 2002 and 2003 seasons, the redesigned planter was used successfully to plant 88 plots— 32 at Tappen each year (Steele et al., 2006) and 12 at Oakes each year. In 2002, plots were on an Arvilla sandy loam (sandy, mixed, frigid Calcic Hapludoll) at Tappen and a Maddock sandy loam at Oakes. In 2003, plots were on an Embden loam (coarse-loamy, mixed, superactive, frigid Pachic Hapludoll) at Oakes and on an Arvilla sandy loam at Tappen. The planter performed as intended with no yielding or failure of structural members. No structural changes were made to the planter in 2003.

The disk closing system was found to be the area most needing improvement for future planter redesigns. Note in figure 5 that a threaded rod was used to adjust the height of the disk closers. No additional adjustments, such as changing the rotation of the disk angle of attack or changing the spacing between disks, were available. Steele et al. (2006) provided a description of temporary modifications to the closing system to better achieve the desired V-shaped furrow. Modifications included dragging a heavy chain behind the disk closers in 2002 and replacing the disk closers with a blade or soil scraping system in 2003.

Second Design Cycle with Student Involvement

Work for the 2004 season focused on redesign of the disk closing system and a three-student capstone design team was enlisted for this task during the 2003-2004 academic year. Lugert et al. (2004) moved the seed carousel forward and reversed it so the seed drop tubes were at the rear of the carousel table (fig. 8). The table reversal reduced the overall length of the planter, reduced the moment on the three-point hitch, and provided more room for the redesigned closing mechanism. The table reversal also placed the seed drop tubes immediately in front of the operators, resulting in easier viewing of the drop tubes. The team redesigned the closing system by adding an adjustable toolbar mounting bracket consisting of adjustment brackets, mount plates, and pivot brackets attached to the rear frame of the planter (fig. 9). The redesign provided more degrees of freedom to adjust the disks on the closing system. The redesigned closing system maintained the design requirement of independent and separate operator access to each seat. Although the 2003-2004 design team had a full academic year to devote to the project, they were not asked to consider a computer-controlled seed spacing system because the ground drive system performed well and they were subject to similar cost, time, and scope-of-project constraints as the 2002 team.

Lugert et al. (2004) used engineering design tools similar to those used by Rockeman et al. (2002) to develop their solution. A decision matrix included two design alternatives and four weighting factors. Design alternatives were 1) a shortened frame with a single toolbar for the closing system and 2) a shortened frame with independent toolbars for each row's closing system and redesigned carousel and operator platforms. Weighting factors were cost, ability to transport the machine without removing the closing disk assembly, overall weight, and operator egress and safety. *Pro-Engineer* software (Parametric Technology Corp., 2000) was used to model parts and assemblies for the design alternatives. The design selected was a compromise to achieve the best features of each alternative. Draft estimates were determined using procedures available in *ASAE Standards* (1997); a fine-textured soil was chosen because it would give the largest draft force and therefore the most conservative design. The resulting forces, moments, and stresses on the disks, brackets, and other parts were calculated using principles of machine design (Young, 1989; Juvinall and Marshek, 2000). The toolbar mounting bracket, adjustment bracket and mount plate, adjustment bar, and pivot bracket designed in *Pro-Engineer* were subjected to finite element analysis of stress and strain (ANSYS, 2001) using Young's modulus and Poisson's ratio from Oberg et al. (2000).

The main advantage of the new closing system is an increase in the number of degrees of freedom of adjustment. The new system provides height adjustment as in the previous design, but provides two means of height adjustment rather than one. The first mode of height adjustment is

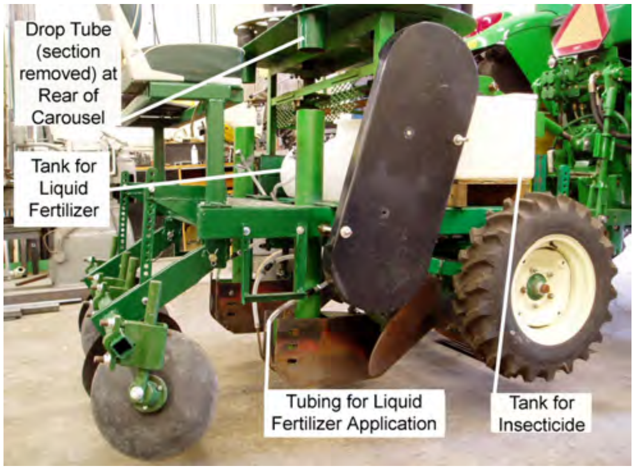

Figure 8. Side view of 2004 redesigned potato planter.

raising or lowering the toolbar by means of an adjustment bracket and the second is movement of the disk mounting rod within its mounting bracket. Spacing between the disks can be adjusted by moving the disk mounting brackets from side to side on the toolbar, which spans the entire width of the machine. The rotation of each disk can be adjusted by turning the disk mounting rod in its bracket.

The closing system performed as intended during the 2004 season. As with the previous student design team, the scope and the time and cost constraints of the project did not allow detailed life-cycle testing and analysis but the planter was subjected to field use. The planter was used to plant 54 plots at Tappen for a study of hill versus hill planting, seed spacing, and nitrogen fertility levels. The seed spacing was adjusted from 0.30 m (12 in.) to 0.23 m (9 in.) by changing one of the sprockets on the carousel drive system. Fertilizer was banded alongside seed pieces through the use of drip nozzles on each side of each shoe of the planter. An electric pump was used to apply 28% urea-ammonium-nitrate (UAN) in liquid form. The UAN was supplied from its own tank. A separate tank was used for the insecticide (Imidacloprid), which was applied via spray nozzles inside the front of the planter shoes to minimize operator exposure.

In addition to using the planter at the Tappen research site, we used the planter for test strips in the potato fields of four local farmers in 2004. Corn stalk residue from the previous crop proved to be troublesome for the planter at one site. The residue tended to lodge under the center of the planter, requiring operators to stop and clean out the excess material before proceeding. Hyde et al. (1977) noted difficulty planting potatoes in settings with a large amount of loose crop residue on the surface. The 2003-2004 capstone team presented their design in an oral presentation near the end of the semester and documented their work with a written report (Lugert et al., 2004).

Suggestions for Improvement

Planter Design

The overall machine weight is perhaps the greatest deficiency of the present design. Furrow planting in 2001 was initially undertaken with a 37-kW International Harvester 606 tractor (46.4 drawbar hp; Tractor Data, 2006), but tire slippage at Oakes led us to use a 50-kW Ford 7000 tractor (66.6 drawbar hp; Tractor Data, 2006) for planting at Tappen. The Ford tractor was satisfactory for planting operations in both the hill and furrow planting modes from 2001 through 2004. Other tractors used successfully for operating the planter in the furrow planting mode at Tappen included a 48-kW John Deere 5420 (65 engine hp; Tractor Data, 2006) in 2005 and a 41-kW Kubota M6040 (55 PTO hp; Kubota Tractor Corporation, 2006) in 2006.

Design and operation of plot-scale potato planters should also consider the following items, presented in no particular order. In-row seed spacing could be changed more quickly with the use of multiple offset sprockets such as those

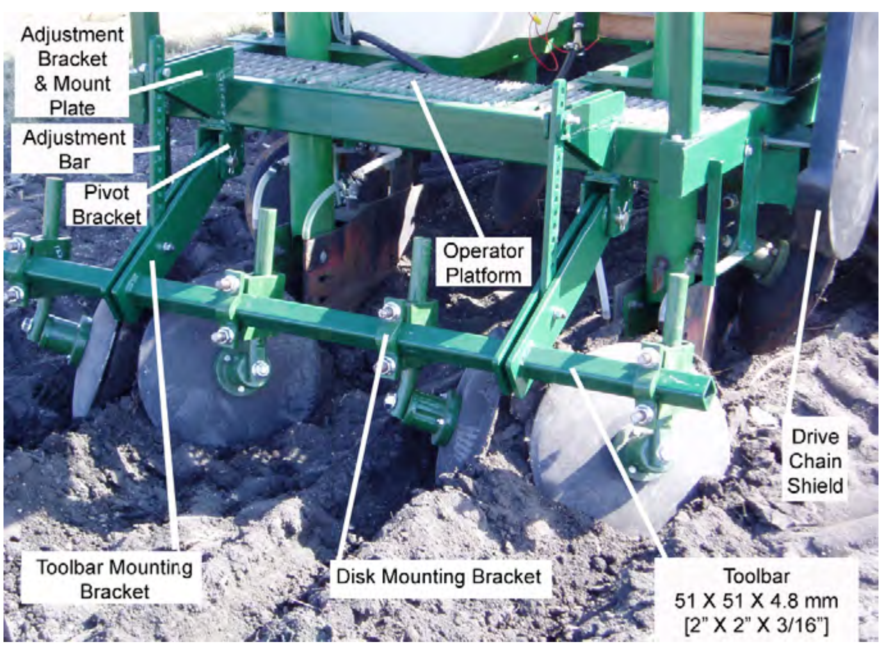

Figure 9. Redesigned disk closing system.

described by Misener and McLeod (1988). Liquid or granular fertilizer delivery systems could be designed for fertilizer placement at various positions with respect to the seed pieces. Adjustment of the ground drive wheels is now accomplished with depth adjustment links (fig. 5), but a crank on a threaded rod (with a locking nut to hold the position) would provide faster and easier adjustments. The tip of the cultivator shovel should be positioned below the bottom of the shoe. Hyde et al. (1977) used a sweep on a spring shank in front of and deeper than the bottom of the shoe when planting in no-till conditions. In 2004 we observed that if the shoe was deeper than the cultivator shovel, the shoe produced a flat and compacted soil surface on which the seed pieces often rolled or bounced, thereby affecting in-row seed piece spacing. When the cultivator shovel was lowered below the shoe, a roughened seedbed floor was produced and the rolling or bouncing of seed pieces was virtually eliminated. Refinements of shoe and shovel positions could be used to study the coefficient of variation of in-row seed spacing (Misener, 1982; Misener and McLeod, 1988). It should be noted, however, that the planter described herein would be difficult to operate at speeds comparable to commercial units.

Instruction

Historically, final oral project reports were presented the week before final exams in the spring semester and the final written project reports were due during the final exam week (mid May). Many written reports were judged to be low in quality and hastily written by student teams seeking to complete the semester and graduate. Submission of reports late in the semester provided no opportunity for feedback and rewriting of the reports. To address this concern, in the 1999-2000 academic year, the final oral reports were moved to the week before spring break, typically early March, with a draft of the final written report required at the time of the presentations. This feedback loop allowed the capstone class instructor and the team's project cooperator to review the report and provide comments and corrections for the team before they submitted their final written report. The first capstone team working on the potato planter did not fall under this schedule because the team was working on the project as a "fast track" where due to previous internships the team members were doing both semesters of capstone work in one semester.

As a result of comments made by capstone design teams, including the second team working on the potato planter, the time for the scheduled final oral presentations was changed from early March to late March or the first week of April to allow the teams a little more time to complete their projects and prepare their reports, but still have time for the review and feedback loop. This has proven to be a reasonable compromise from the perspectives of both the capstone course instructor and the student teams. Teams are busy, but the project does not intrude into the finals week of the spring semester.

During the past two years, graduate students from the Communications Department at NDSU have been asked to provide comments and feedback on capstone design team presentations at three stages of project development. These stages are the fall semester presentations of project proposals, the spring semester poster session in February, and two sessions with the final spring semester presentation (to assess slide content and the overall presentation).

Safety Considerations

Design, construction, and operation of a potato planter poses inherent hazards of entanglement of clothing and bodily parts, exposure to insecticides and other chemicals, and possibly other risks not mentioned in this article. Those involved in design, construction, operation, and other aspects of use of the planter are hereby advised to follow applicable safety codes and considerations and to construct and use the system at your own risk. THE PLANTER DESIGNS DEPICTED HEREIN ARE EXPERIMENTAL, AND THE AUTHORS MAKE NO WARRANTY, EXPRESS OR IMPLIED, AS TO THE OPERATION OR SAFTEY OF THE PLANTERS.

For safety, guarding shall be used for all sprockets, chains, gears, carousels, wheels, motors, spray nozzles, etc. in accordance with applicable standards (*ANSI/ASAE Standards,* 2003). Safety features shall be incorporated into the planter design in accordance with ANSI/ASAE (*ANSI/ASAE Standards,* 2002). A readily accessible and easily operated power disconnect switch for chemical application pump(s) shall be provided for operator safety. Proper grounding procedures for electrical components and isolation from shock hazards must be followed. Safety alert and warning signs shall be placed on the planter to indicate hazards of clothing, finger, hand, or leg entanglement caused by the moving parts (SAE, 1991; *ASAE Standards,* 1999). Chemical application equipment shall be calibrated and used in accordance with applicable engineering practices (*ASAE Standards,* 2003; *ASABE Standards,* 2007a). Chemical selection, mixing, application, disposal, and related activities shall be conducted by appropriately-trained individuals and shall conform to applicable federal, state, and local regulations.

Conclusions

Undergraduate engineering students successfully redesigned and rebuilt the two-row potato planter so it could operate in both furrow and hill planting modes. The planter performed as expected during the 2002 and 2003 seasons and had no mechanical failures. The modified closing system performed as expected in 2004 with no mechanical failures. One operator of the planter noted that consistent seed piece size seemed to be important to the operation of the planter and that adjustments in the closing system were easier to make in later versions of the planter compared with earlier versions. Another operator noted that seed piece depth control was good with the 2002 addition of the adjustable depth control mechanism.

External projects provided to the capstone design class, such as the potato planter modifications, allow students to have "hands on" experience. Brainstorming alternative potential solutions, analysis, and evaluation are combined with actual fabrication and construction of a system. Capstone design teams experienced the reality that what looks good on paper or the computer screen does not always come out as planned in actual construction. Multiyear projects such as the potato planter allow student design teams to evaluate the performance of past designs, see the need for improvements, and see that design is frequently an ongoing, incremental process.

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