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Potato Planter Development via Capstone Design and Engineering Tools

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Abstract. *A multi-year research project comparing potato planting configurations required a mechanical, plot-scale (two-row) planter capable of planting in both a conventional (hill or ridge) mode and in a furrow or trench mode. The objective of this project was to enlist teams of undergraduate engineering capstone design students to redesign and modify a conventional potato planter into a unit capable of planting in both furrow and hill modes. 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. A local manufacturing facility laser cut some of the parts based on three-dimensional computer-aided design models developed by the students. The second team of students (two years later) redesigned the disk closing system and shortened the overall length of the planter. Students conducted stress analyses based on their three-dimensional models of the planter. Both planter redesigns were used successfully in the field for small plot experiments. This paper will present our experiences in the roles of 1) research project leader and 2) capstone design course instructor.*

Keywords. undergraduate education, computer aided design, agricultural machinery, research

Introduction

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. This article presents the need and design constraints for a plot-scale potato planter capable of planting in both hill and furrow configurations, chronicles the redesign and modifications made to an existing planter by teams of undergraduate engineering students, reports the results achieved and improvements made over multiple seasons of field use, suggests areas for improvement, and notes safety considerations. We used the field planter in field studies (Steele et al., 2006).

A variety of seedbed geometries or planting configurations have been studied for potatoes, including wide beds (Mundy et al., 1999); "quad" planting (Bouman, 1998); and conventional hill or ridge planting with dammer-dike, a smaller hill with a shallower furrow, and flat planting (Alva et al., 2002). Hill vs. flat planting has been studied by Sharma and Dixit (1992), Sharma et al. (1993), and Lewis and Rowberry (1973). Agassi and Levy (1993) studied furrow diking vs. conventional cultural practices. Gupta and Singh (1994) and Steele et al. (2006) compared hill and furrow planting, while Arshad et al. (1999) compared hill, furrow, and flat planting. Tian et al. (2003) compared yield responses and rainwater harvesting effects for potatoes planted in three configurations, i.e., furrow planting with mulched ridges, furrow planting with bare ridges, and flat planting.

Commercial potato planters such as Harriston (Harriston/Mayo, Minto, North Dakota) or Lockwood (TerraMarc Industries, West Fargo, North Dakota) 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 17-inch row spacing with four or five rows per bed, or planting into pre-marked rows (D. Dunnigan, 2005 personal communication, Harriston Company, Minto, North Dakota). 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 given by the coefficient of variation (CV) for seed spacing. Arsenault et al. reported similar design features on their planter and reported lower CVs for seed spacing than Misener and McLeod. The Arsenault et al. planter was a flat planter with hill formation conducted as a separate operation after planting.

The objectives of this project were to: 1) redesign a two-row potato planter so it could plant in both hill and furrow configurations for plot-scale research studies, and 2) provide design opportunities for undergraduate engineering students. Design considerations and operating constraints included 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 present 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 present 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 and used for research purposes only. The design modifications and corresponding results are presented in chronological order for ease of reading. We also present a summary of student instruction.

Design Modifications and Results

We used small plot field studies in North Dakota, USA to compare hill vs. furrow planting configurations for potatoes (Steele et al., 2006). Potatoes for all plots and years were planted with a 0.91-m (36-inch) row spacing with 0.30-m (12-inch) seed spacing in the row. Plots were four rows wide by 12.2 m (40 ft) long. Trials were conducted at the Oakes Irrigation Research Site [46º04' N latitude, 98º06' W longitude, and 396 m elevation (Enz et al. 1997)] and at potato research sites near Dawson (46º55' N latitude, 99º46' W longitude, 530 m elevation) and Tappen (46º53' N latitude, 99º35' W longitude, 543 m elevation). Soil descriptions are provided in the context of the yearly narratives 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 but provides sufficient time for accurate manual seed placement on research plots.

Year 2000

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 (Figure 1). The disk openers were obtained from Lockwood (Crary/TerraMarc Industries, West Fargo, ND) potato planters. 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, and insecticide was applied using a portable, hand-operated spray unit. 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 (Figure 2) for the furrow planting trial. 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.

Year 2001

We obtained access to a custom-built two-row planter (Figure 3) which served as the base unit for subsequent design modifications. The unit was patterned after Iron Age models, 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-inch) diameter rotating aluminum carousels with 18 holes around the perimeter. The carousels are driven together from the right wheel through a system of sprockets, chains, and gears. A table under the carousel 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. The larger carousel allows the operators to easily skip seed pieces when changing cultivars, a task not practical with a pick-type planter. The shoe-type opener in front is similar to those used on Lockwood planters.

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 above the table 11 cm (4.5 inches) (Figure 4) and the covering shield removed. An extension drop tube was constructed for each hole and consisted of steel conduit 7 cm (2.75 inches) in diameter and 5.1 cm (2 inches) 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 inches) 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 preferred over the safety hazard that would have been present had the table not been raised.

The disk openers used in 2000 were mounted on the front of the planter to enable furrow planting. For each row, the original planter had a vertical support structure (Figure 3) consisting of 13-mm (0.5-inch) flat steel welded between the 102-mm by 102-mm by 4.8-mm (4 inch by 4 inch by 3/16 inch) main front frame member and the top of the shoe. A horizontal mounting structure (Figure 4), also made from 13-mm thick plate steel and approximately 305 mm (12 inches) long and 102 mm (4 inches) high, was bolted to the vertical support structure and used to mount the disk hardware for each row.

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 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 rolled over by 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 behind the tractor tires, i.e., over undisturbed soil, and had negligible soil adhesion.

At the Dawson site, plots were located on a Towner loamy fine sand (sandy over loamy, mixed, superactive, frigid Calcic Hapludoll). To overcome the soil adhesion problem encountered at

Oakes, we removed the ground drive wheels and used a hydraulic motor to drive the carousel (Figure 4). 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.

The disk opening system on one side of the planter yielded during planting operations at Dawson. The failure consisted of a bend of approximately 19º 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.

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.

Year 2002

Following is a brief description of significant modifications in the planter accomplished by Rockeman et al. (2002). Wheel assemblies were designed to position the ground drive wheels in front of the disk openers to avoid compaction of the midrow ridge (Figure 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 (Figure 6). The front ends of the furrower structures were designed to hold mounting brackets for furrowing shanks equipped with cultivator shovels (Figure 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.

The redesigned planter was used successfully for the 2002 and 2003 seasons. The planter performed as intended with no yielding or failure of structural members. In 2002, plots were on a Maddock sandy loam at Oakes and on an Arvilla sandy loam (sandy, mixed, frigid Calcic Hapludoll) at Tappen. 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. No significant design 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 and replacing the disk closers with a blade or soil scraping system.

Year 2004

Lugert et al. (2004) redesigned the closing system for the potato planter. The carousel was moved forward and reversed, with the seed drop tube now at the rear of the carousel table (Figure 8), i.e., immediately in front of the operators. This reversal provided more room for the redesigned closing mechanism, reduced the moment on the three-point hitch, and reduced the overall planter length. An adjustment bracket, mount plate, and pivot bracket were added to the rear frame of the planter to provide an adjustable toolbar mounting bracket (Figure 9).

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 raising or lowering the toolbar by means of an adjustment bracket and the second is movement of the disk assembly 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. A study of in-row seed spacing and N fertility levels was conducted at the Tappen research site. 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 electrical 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.

Student Instruction

The North Dakota State University (NDSU) Agricultural and Biosystems Engineering (ABEN) Department's capstone design experience 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 systems, biomaterials systems, 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 your 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.

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) experiences. 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.

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 team developed a ground drive using sprockets and chains to replace the hydraulic motor drive unit and developed new disk mounts and a furrowing shank mounting structure. 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 $1,000 (Rockeman, 2002).

Weather conditions in the spring of 2002 did not allow the team to test their prototype during the semester. However, the prototype was used after the semester ended and performed satisfactorily. No yielding or failure of structural components was observed during the 2002 and 2003 seasons.

Modifications to the potato planter were proposed to another capstone design class for the academic year of 2003-2004. A three-student team was formed to redesign the disk closing system. The redesign of the disk closing system included the following modifications to the planter (Lugert et al, 2004): 1) moving the planting carousel forward and reversing it so the seed drop tubes were at the rear of the carousel table to provide space for the closing system; 2) providing more degrees of freedom to adjust the disks on the closing system, and 3) allowing the operators separate access to their stations. The planter was successfully redesigned by the students and used for field studies in the 2004 and subsequent seasons.

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. Both potato planter teams used Pro-Engineer software (Parametric Technology Corp., 2000) to develop alternative designs (Figure 10) for the potato planter. The parts designed in Pro/E were subjected to finite element analysis (ANSYS, 2003) of stresses and strains expected for the structural members of the planter. Some parts used for the 2002 modification of the planter were laser cut by a local manufacturing company using the Pro/E models developed by Rockeman et al. (2002). Capstone design teams experienced the reality that “what looks good on paper or the computer screen” does not always come as planned in actual construction.

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, 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 described by Misener and McLeod (1988). Adjustment of the ground drive wheels is now accomplished with depth adjustment links (Figure 5), but a crank on a threaded rod 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 placement positions could be used to study the coefficient of variation of in-row seed spacing (Misener, 1982; Misener and McLeod, 1988), although the planter used in this study, traveling at approximately 0.45 m s^{-1} (1.0 mph) or slower, would be difficult to operate at speeds comparable to commercial units [e.g., 2.9 m s^{-1} (6.5 mph) (Fairbourn, 2007)] because hand placement of seed pieces could not keep up with the angular velocity of the carousel. Liquid or granular fertilizer delivery systems could be designed for fertilizer placement at various positions with respect to the seed pieces.

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 paper. 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 SAFEY 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, 1998). Safety features shall be incorporated into the planter design in accordance with ANSI/ASAE (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, 1999).

Conclusion

Undergraduate engineering students successfully redesigned and rebuilt a two-row potato planter so it could operate in both furrow and hill planting modes.

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Figures

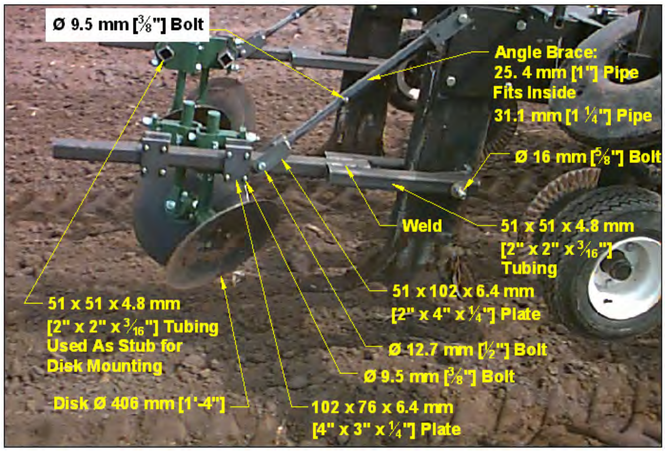

Figure 1. Side view of toolbar designed for installation of subsurface drip irrigation tape and equipped with disk openers for furrow formation.

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

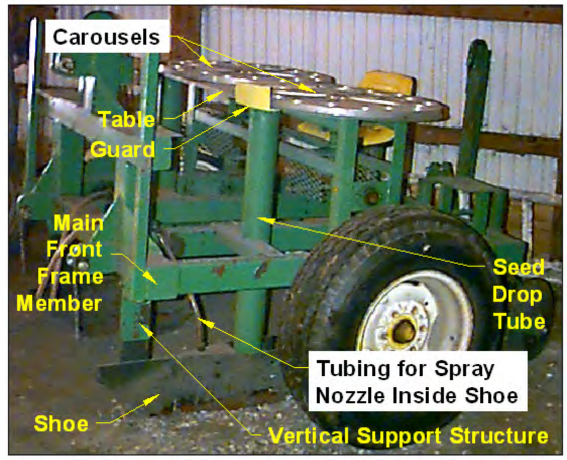

Figure 3. Custom-built two-row planter for mini-tuber unit planting (near operator seat is missing).

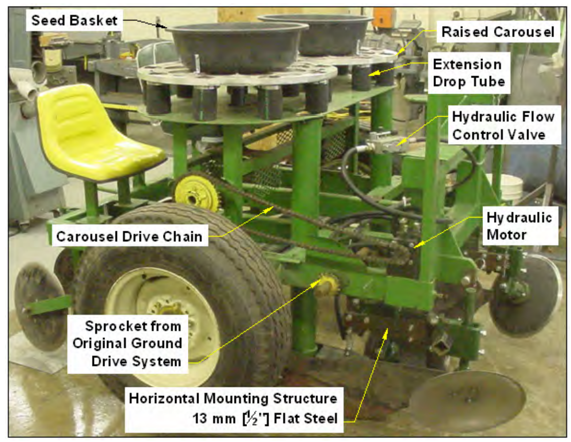

Figure 4. Modified potato planter used in 2001. Shields have been removed to show details.

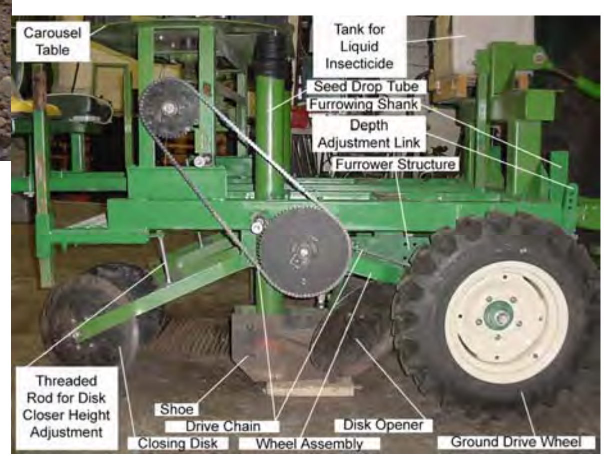

Figure 5. Potato planter after redesign in 2002 (gear and chain shield removed to show details).

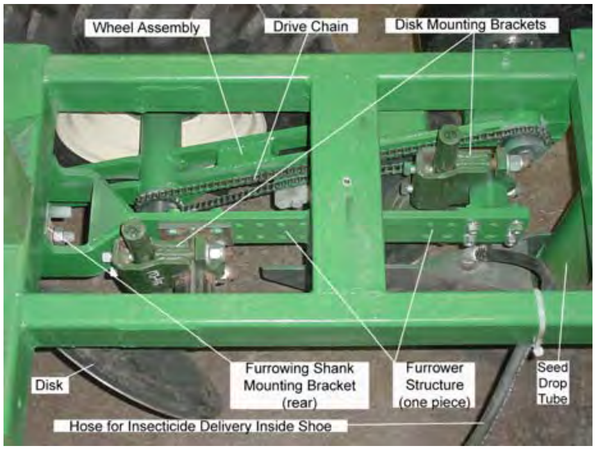

Figure 6. Furrower structure detail.

Figure 9. Redesigned disk closing system.

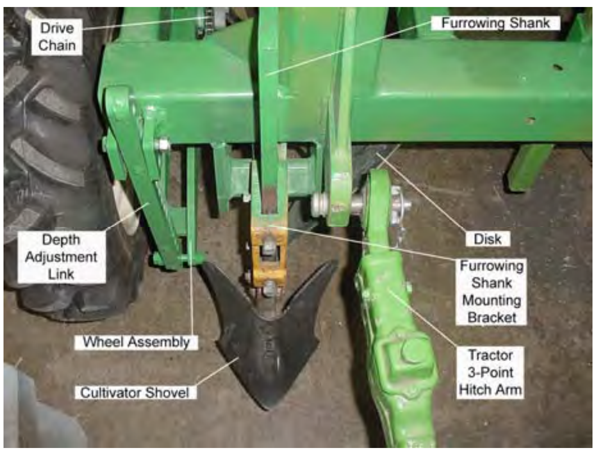

Figure 7. Front view of furrower structure and mounting bracket for cultivator shovel.

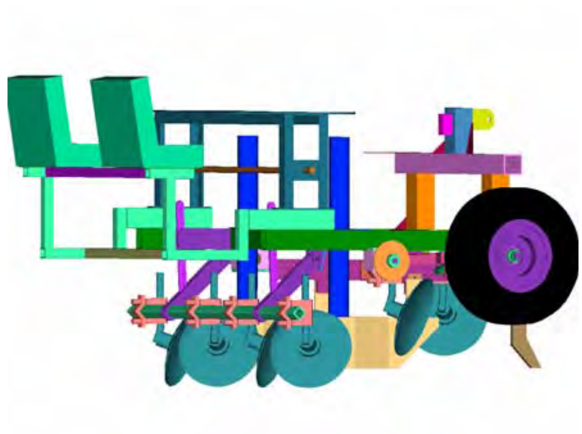

Figure 10. Computer-aided design model of an alternative design for the potato planter.

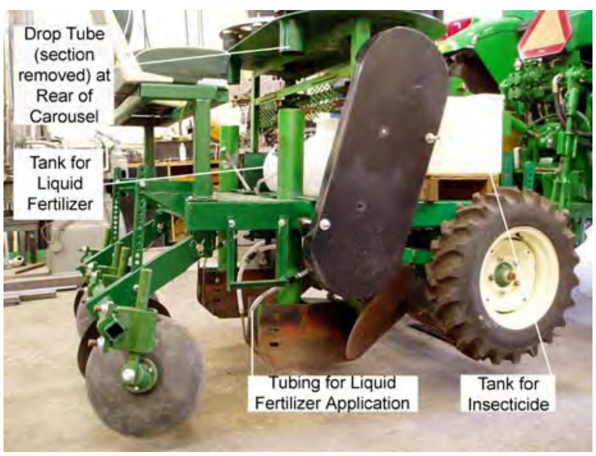

Figure 8. Side view of 2004 redesigned potato planter.