Design of a market-ready tractor for small farms in low- and middle-income countries

by

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Abstract

This paper presents the design, testing and user feedback of a new prototype of a tractor platform intended for use on small, resource-constrained farms. This development builds on past work by implementing several upgrades which promote market competitiveness and maximize functionality, ergonomics, and aesthetics. Stakeholder discussions, review of prior art and recommendations from past authors were used to draft new functional requirements for a better vehicle. Hydraulic power systems were implemented that significantly improve user comfort by automating repetitive or unwieldy tasks. Newly designed crop-spraying solutions based on feedback from farmers allowed the tractor to perform crop maintenance functions that larger vehicles cannot while also reducing worker exposure to harmful chemicals. A rear-oriented PTO was installed to allow the vehicle to power external implements. A redesign of a stabilizing solution increased the vehicle's versatility in managing various crops and transit between properties. The upgraded vehicle was tested in Massachusetts and validated by stakeholder surveys in India. Farmers from Massachusetts and from The Philippines who tested the vehicle responded positively. They indicated the tractor would be a valuable addition to their small farms and would substantially reduce drudgery. Testers believed the format of the vehicle was familiar, easy to learn, and comfortable to ride. This paper demonstrates that two-wheeled tractors are not only viable, but can produce the same utility as conventional tractor layouts at a significantly lower cost.

Thesis Supervisor: Amos G. Winter V
Title: Associate Professor

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Chapter 1

Introduction

1.1 The need for low cost farm machinery in low and middle income countries

Low- and middle-income countries (LMICs) play a significant role in global food production. As of 2021, they were home to 73% of global farmland [1, 2] and produced 71% of the world's cereal [3, 4]. LMIC also produces less crop per unit area than countries with modern agricultural technologies [5–8]. Significant portions of this yield gap are due to poor crop management [9, 10]. Modern methods (such as precision agriculture, drip irrigation, etc.) improve the production rate of farmland in these areas [11], but these methods are more complex and require additional labor or significant capital [12] and are unrealistic for many small farms ($\leq 2ha$), which account for 84% of global farms [13]. Instead, small farms in LMICs rely heavily on costly manual and animal labor for agricultural work [14, 15]. Mechanization of farms is known to be prudent in reducing this yield gap, while also promoting general welfare in the community [16],[17]-[18]. Addressing this yield gap is important for ensuring continued global food security [7, 8, 19].

India is especially well-suited for mechanization due to a declining workforce, a steep rise in adoption of technology, and several government and industry incentives. As of 2021, 44% of its 1.4 billion people work in agriculture [20]. This workforce is declining as the Indian middle class grows [21]. In recent years, children from farms are becoming more educated and seek white-collar work in cities [22]. Workers are turning away from seasonal labor, which is seen as unreliable. The migrant labor force was also significantly impacted by Covid-19 [23]. Adoption of smartphones in india has skyrocketed in recent years [24] and grown especially among rural Indians in particular [25],[26]. This has created access to new technology and information for farmers [27], [28] and caused a societal shift in which workers who were previously skeptical of machinery are now excited to incorporate it [29].

Many farmers in India lack access to financing institutions to support farm equipment lending [30], [31]. The government of India is addressing this by subsidizing farm equipment in whole or in part [32]. Manufacturers address this by offering in-house financing [22]. Despite the benefits of mechanization, it is largely seen as inaccessible by global smallholder farmers. Figure 1-1 describes five classes of tractors with example products and their cost. Many of the vehicles described are not affordable with or without financing for the average Indian small farm owner, who has an annual income of 120,000 INR (1500 USD) [33]. Even if financed, a 7-year loan on a $5000 vehicle at 4.5% interest would require a monthly payment of $69.50. Over the course of the year, this is over half of the farmer's income.

Eighty six percent of farms in India are less than 2 ha in size [14] and have very little spending power. Compare this to the US where the average farm is 185 ha [34, 35] and average farm income is 185,600 USD (15.2 million INR). Ninety eight percent of US farms are family owned and operated [36]. The average US farm is a small but wealthy workforce interested in maximizing the productivity of an individual worker. This creates a development incentive to focus on large, expensive, single-operator machines like the John Deere DB120, which can plant 40 ha of crop per hour and costs over 1 million USD [36]. This is an extreme case but demonstrates a market of expensive machines that are obviously not reasonable or affordable for the smallholder scale. Smallholder farmers instead opt for draft animals [14, 37] which are less expensive up front but cost significantly more annually [37, 38].

Ownership of a tractor also requires an ability to maintain it over its lifetime. This

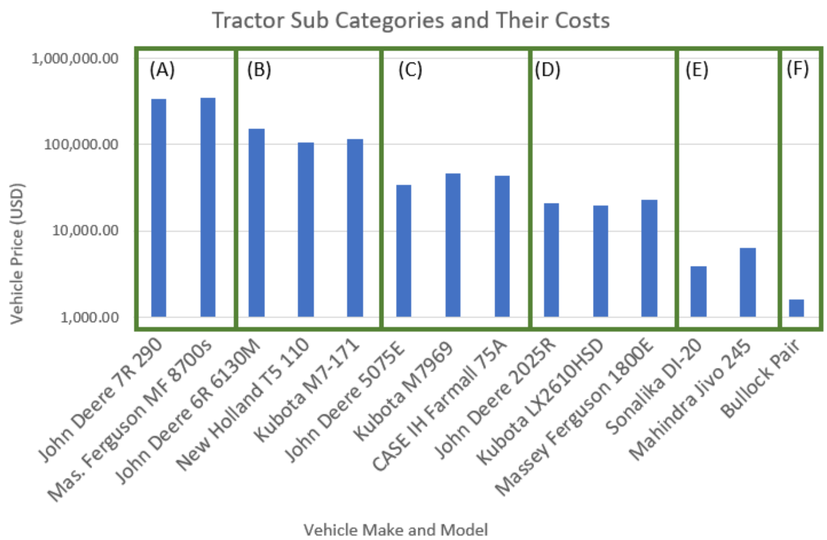

Figure 1-1: 2022 production year tractors and their approximate costs. Vehicles are categorized as follows: A) Ultra-high-performance vehicles with high horsepower and automation technology. B) General purpose, high-power tractors. C) Multi-purpose utility class tractors. D) Compact and subcompact tractors appropriate for landscaping. E) Affordable small machinery. F) Animal Power.

requires significant industrial infrastructure, including transportation of the vehicles, a supply chain of parts for maintenance, and skilled mechanics capable of performing that maintenance. The rural regions of India are developing this infrastructure, but its current capacity is lacking [22].

The high costs of a mechanized alternative aside, farmers have indicated several advantages of owning draft animals. Draft animals can walk a very narrow path, allowing crops to be planted close together [38]. They can also turn in place from a standing position, reducing the need for significant headland area (area left unplanted at the edges of a field for turning around) [38]. The excrement from draft animals is a valuable source of cooking fuel and fertilizer [22]. A bullock pair costs on average $1600 USD, and they offer about 10 years of service [22]. This is considered affordable by smallholder farmers [38].

The Indian Agricultural Ministry projects that use of tractors can reduce wasted fertilizer and seed by more than 15% [14]. Farm labor can be reduced by more than 20% [14]. The cost of ownership of a tractor in a 15-year period may be less than half the cost of owning a bullock pair for the same time [37]. There is a growing market for low-cost, high-performance vehicles, that is currently unserved. To address this market gap, alternative solutions and their shortcomings must be considered.

1.2 Attempts to bring farm machinery to low and middle income countries

Several businesses and communities have attempted to fulfill the need for mechanization in small farm agriculture. Tractor hiring is one service that has become prevalent across the world, largely driven by labor shortage [39]. In a tractor hiring service, an operator will purchase a tractor and use it to perform farming operations in exchange for pay [22, 40]. Common operations include plowing and tilling (which require the most physical labor) but may also include spraying, planting, and harvesting. This generates significant added income for the owner who may service between 10 and 150 ha/yr as well as any land they own themselves [40]. In India, a farmer may expect to pay 1000-2000 INR per ha, per operation. This price varies regionally [22]. Unfortunately, availability of these services is often limited, as the ratio of farmers to service providers may well exceed 100 [40]. This creates long wait times that may be detrimental to the crop. Despite this, hiring services are believed to be critical for mechanization development in LMICs [41–43].

Other farmers may service their needs with "Jugaad" implements. "Jugaad" is a Hindi word which describes something that is unconventional and frugally made. Jugaad farm implements are locally manufactured from available materials and sold for a very low price. They are often single-purpose and consist of small engines mounted to welded steel frames (Fig. 1-2). These implements are sold for 15000-50000 INR (200-600 USD). Their effectiveness is inferior to conventional tractors but reduces the drudgery of manual laborer.

The Jugaad tractor format commonly takes the form of a so called "walk-behind" tractor, which has been adopted by larger manufacturers as an alternative to tractors.

Figure 1-2: A jugaad tractor equipped with blade harrow.

One example is the E-Agro Care "Power Weeder" (Fig. 1-3) which can perform weeding and light tillage. Because it generates very low forward force, it relies on high-speed operations like rototilling. It can be purchased for around 110,000 INR (1300 USD) [44].

Many India-based manufacturers are cognizant of small farmer's needs and have begun producing ultra-low-cost tractors to fill this market gap. These vehicles (like the Sonalika GT-20 and the Mahindra JIVO 245 (Fig. 1-1E) share the conventional, 4-wheel layout of a typical tractor, but may lack many modern conveniences like power steering, lights, or power take-off (PTO). PTO is a mainstay in modern machinery that facilitates power delivery from the engine to a rear-mounted implement via a rotating shaft connected to the tractor's rear driveline. Implements like rototillers, mowers, and silage choppers are often powered by PTO.

Past work by our research group developed the prototype "Bullkey" tractor (Fig. 1-4): a prototype vehicle intended explicitly to address the smallholder farm market as a high-performance alternative to jugaad machinery and draft animals at a similar price point. Discussions with stakeholders, including farmers, salesmen, and manufacturers

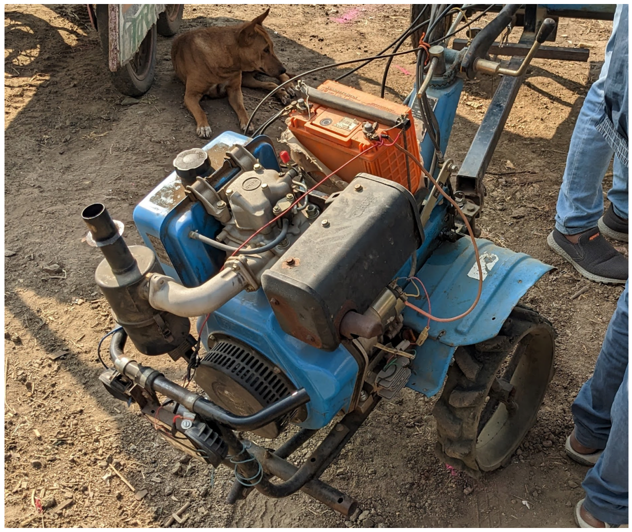

Figure 1-3: (TOP) E-Agro Care Power Weeder. A two-wheel, walk-behind tractor. This tractor was purchased by an Indian farmer and entirely subsidized by the Indian Government.

in India outlined farming operations that a tractor should be able to perform. The Bullkey Tractor performs all these operations equal to or better than draft animals. It is projected to cost only slightly more than a bullock pair, and the annual costs are substantially lower [38].

The Bullkey tractor sports a novel layout for agricultural machinery. The base vehicle is a 2018 Rokon Scout (Rokon, Rochester, NH). The two-wheel, motorcycle-like format creates advantageous soil interaction that drastically outperforms two-wheeled, walk-behind tractors [37]. The vehicle is also two-wheel drive, which generates significantly more forward traction than if the same amount of power was delivered only to a single wheel [37]. A center-mounted plow distributes the vertical component of plowing forces to both wheels of the vehicle. This causes the tractor to emulate a heavier vehicle during plowing, where weight is beneficial for traction [37, 38]. Front and rear weight racks allow the operator to add ballast weight to control tire slip in a variety of soil conditions.

The vehicle may be stabilized while moving slowly either by an outrigger wheel (OW) (Fig. 1-4) or the "balance board": a set of wheels which are not rotationally constrained to the vehicle and allow the operator to exert force on the ground to

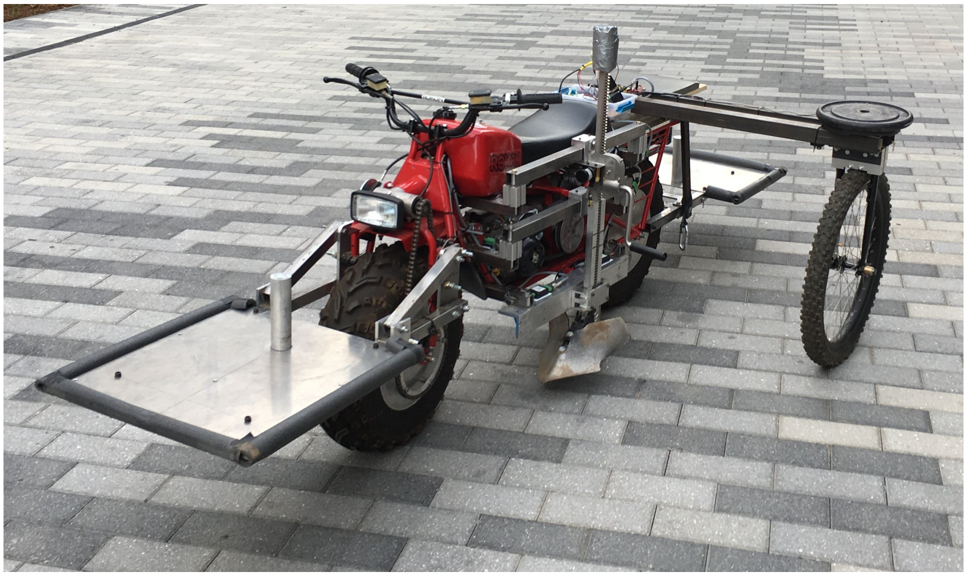

Figure 1-4: The original Bullkey prototype with weight racks installed on the front and rear, and supported in roll by the outrigger wheel attachment

keep the vehicle upright while in motion [38]. An electric 3-point hitch (3pt) was installed on the rear of the vehicle. A 3pt is a standard connection that allows for 3rd parties to design implements like tilling tools and harrows that interface with the vehicle. Implements attached to the 3pt can be raised and lowered as necessary to create ground clearance.

The Bullkey platform also addresses industrial infrastructure concerns. Seventy five percent of all vehicles in India are two-wheelers [45]. The motorcycle-layout of the vehicle is familiar to mechanics and operators alike, and a supply chain of motorcycle parts already exists.

The prototype was assembled and tested in Massachusetts and validated by stakeholder interviews in India. Stakeholders responded positively to photos, videos, and descriptions of the vehicle's functionality, indicating their interest in adopting it should it become available [38]. Farmers also indicated that the Bullkey seems ideal for spraying orchards and tall crops, as it can maneuver close to trees and between rows of crops without damaging them. These operations are currently performed by laborers with knapsack sprayers. The labor is expensive and the sprayers are often wasteful [14, 22].

Figure 1-5: A test-rider operates the original Bullkey vehicle side-saddle. The height control prevents them from straddling the vehicle.

The Bullkey prototype suffers a few ergonomic and functional shortfalls. The center mounted plow prevents the rider from sitting conventionally, forcing a "side-saddle" position (Fig. 1-5). The plow is raised and lowered via a rack and pinion cranked by a large arm. This is a tiresome, repetitive motion that is especially uncomfortable while riding side saddle. The vehicle's 3pt sits very far to the back of the vehicle. Any loads on the 3pt generate a large tipping moment, requiring significant added ballast to the front. The outrigger wheel attachment is rigid and cannot be removed easily. Farmers indicated in surveys that they would prefer an adjustable OW to accommodate crops with various spacing. It is also desirable to easily remove the OW and store it on the vehicle for transit, as driving with the OW on busy roads could be dangerous. Test-riders of the vehicle often complained that the weight racks (Fig. 1-4) were dangerous tripping hazards. The tractor does not include a PTO, which is important for powering many farm implements.

An improved Bullkey tractor would address these concerns. The sitting position would be more ergonomic for the rider, and tedious operations like cranking the plow height adjustment would be eliminated. The 3pt would be brought closer to the rear wheel to increase weight capacity, and a PTO would be installed to bolster the overall functionality of the vehicle. Redesigned spraying systems would accommodate farmer's suggestions about orchards and tall crops.

Over the course of this study, the authors regularly consulted Indian stakeholders with the support of the SM Sehgal Foundation, an India-based NGO which supports agricultural development in India. The authors hosted informal group discussions in the Telangana, Maharashtra, and Haryana regions of India. The goals of the project were described to attendees, who were then shown photos and videos of the original prototype. The authors engaged in discussion about local farming practice, economics, and the farmers' expectations for the performance of a tractor. The original Bullkey prototype demonstrated the concept's ability to generate drawbar force sufficient for plowing. However, during these conversations, it became clear that end users see tremendous value in the versatility of a modern tractor, not just its ability to generate drawbar force.

In order for the Bullkey tractor to be competitive with modern tractors, it must also demonstrate this versatility. The objective of this study is to implement the upgrades identified by stakeholders and prior testing, which include a plow and 3pt with powered actuation, a rear-oriented PTO, two spraying systems and a redesigned OW with tool-less, adjustable width and storage on the vehicle for transit. The preeminent challenge in this process is packaging these subsystems onto the Bullkey's small platform. The weight, cost and envelope of each upgrade must be coordinated to ensure the vehicle is affordable and convenient to use. Special attention must be given to the locally available resources and manufacturing methods in rural areas of target countries like India to ensure the vehicle is maintainable and repairable.The new machine elements must support high, dynamic, load-bearing, and load-actuating capacity, relative to their size, requiring careful consideration of core engineering design principles.

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Chapter 2

Design Improvements for the Bullkey Tractor

In considering the upgrades to the vehicle, design decisions were made with consideration to three key attributes: cost, weight, and ease of repair. Consequently, the upgrades are fabricated from thin-walled, welded-steel construction, plate stock and simple joints. Mild steel is globally ubiquitous, durable and repairable. To reduce supply-chain stress, parts for these upgrades are designed to be locally manufacturable and do not require CNC capabilities of any kind.

2.1 Design Improvements

In considering the upgrades to the vehicle, design decisions were made with consideration to three key attributes: cost, weight, and ease of repair. Consequently, the upgrades are fabricated from thin-walled, welded-steel construction, plate stock and simple joints. Mild steel is globally ubiquitous, durable and repairable. To reduce supply-chain stress, parts for these upgrades are designed to be locally manufacturable and do not require CNC capabilities of any kind.

2.2 Outrigger Wheel (OW)

Being two-wheeled, Bullkey requires operator effort to stay upright at low speeds. The OW stabilizes the vehicle under these circumstances but may be dangerous on busy roads or at high speeds. In a stakeholder survey, Farmers also criticized the fixed length of the original design [1], as various crops require different spacing between them and the fixed length OW may not adequately straddle certain crops.

An ideal OW would support tool-less installation and adjustment and have an adjustable range between .2m and 1.4m from the edge of the bike [1]. As farmers may be inclined to sit or carry cargo on the OW, it should support a load of 300lbs applied anywhere along its length and support up to 60 lbs. of ballast to prevent the vehicle from tipping away from the OW while cornering.

A simple, sliding OW was designed which supports the suggested range. A long, sliding rail with a 26" wheel on one end is nested between two fixed guide rails. The guide rails have a pin hole at each end, while the sliding rail has pinholes every 3 inches along its length. The sliding rail can be moved in or out of the guide rails and secured in position with a pin (Fig. 2-1). When not in use, the sliding rail can be removed, inverted, and reinstalled. In this configuration, the wheel is off the ground (Fig 2-2), visible to other vehicles and safely within the envelope of the vehicle. The wheel may also be removed from the sliding rail if the operator prefers.

2.3 Three Point Hitch (3pt)

A 3pt consists of two rotating, "lower links" that support the weight of an implement mounted to the rear of a tractor. The distal end of the links can be raised or lowered to adjust the height of an implement or create ground clearance for transit. A "Top Link" connects a third position of the implement to a point higher up on the vehicle and prevents the implement from tipping away from the vehicle. 3pt's are available in five standardized weight classes: Category 0, 1, 2, 3, and 4, where 0 is the smallest and 4 is the largest [2]. The 3pt can be raised, lowered, held at given height, or

Figure 2-1: A closeup of the outrigger wheel. The pin which fixes the length is circled in red.

"floated". A floated implement is subject to external forces and not fixed in place, allowing it to drop under gravity or raise and lower according to contours in the land it rides on.

The heaviest implement used in testing of the original prototype was two plate planters filled with seed. This implement weighed approximately 280 lbs. An improved system would accordingly support weights of up to 300 lbs. The combined weight of the vehicle and the operator generates approximately 700 ft-lbs about the rear wheel, so a new 3pt should also support this moment load. The system should have a vertical range of motion of at least 12". It would conform to the Category 0 standard so that it is compatible with all Category 0 implements. Category 0 was selected because it conventionally supports loads no more than 500lbs. The height of the implement mounted to the the new 3pt would be discretely controllable as with all other 3pt's and it would support "float" functionality.

A highly-compact, 6-bar, single degree-of-freedom linkage was selected to convert power from an input linear actuator into upward force at the lower links. The geometry was expressed as a linear system and solved in MATLAB R2021B (Mathworks, Natick, MA). With the geometry solved, the linkage can be treated as a static sys-

Figure 2-2: Various Positions of the Outrigger Wheel. (TOP) The outrigger wheel in "stowed" position. (CENTER) The outrigger wheel fully extended. (BOTTOM) The Outrigger wheel tight to the frame.

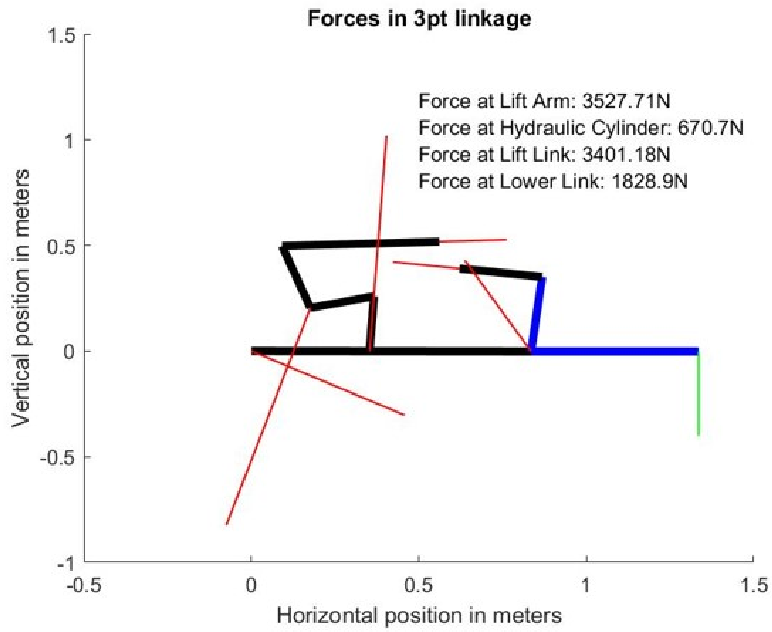

Figure 2-3: Example output of load solver for 3pt. Links are shown in black, input force in green, resultant forces in red, and implement in blue.

tem with one input (A force/moment couple representing the combined weight of the implement and any loads on it) and the forces in any joint can be solved. Figure 2-3 depicts a sample output of this code. Using this model, variations in geometry and load (as well as the resulting reaction forces) can be iterated and visualized with the goal of minimizing static forces in the linkage and maximizing range of motion. Eliminating these large forces reduces cost and weight by keeping structural elements small.

Various methods were considered for driving the linkage. Manual operation requires few complex parts but would be tiresome to use. Electrically driven mechanisms do not support the float function. Hydraulic power, while the most difficult to design an implement, was selected for this application as it can generate tremendous forces and float function is easy to implement. The design of the hydraulic system is described in detail in section 3.6. A small hydraulic cylinder was selected to drive the system [3] and various modifications to the frame were planned to accommodate mounting points for the linkage. All parts were designed in SOLIDWORKS 2021 (SolidWorks Corp., Waltham, MA). This model is shown in Fig. 2-4. Joint reaction forces from the MATLAB model were used to validate the integrity of the designed components using FEA in the SOLIDWORKS Simulation package (SolidWorks Corp., Waltham, MA). The new, highly compact design brings the load an estimated 37% closer to the vehicle than the previous prototype, reducing moment loads accordingly.

There is one linkage on each side of the vehicle. The linkages are actuated simultaneously by a single, centrally mounted hydraulic cylinder. This architecture was selected for a number of reasons: First, the single-actuator design forces the two lower links to move in unison, keeping the implement square with the vehicle. Second, because the frame of the system straddles the vehicle, it is inherently constrained in the transverse axis of the vehicle. This feature, combined with purposeful use of heim joints, prevents the swaying lower links from transferring any transverse loads to the lift arms. In effect, this means that tall, narrow cross sections can be used because bending moments can only be applied in a single direction. By reducing unnecessary bulk, cost and weight are minimized.

2.4 Plow Linkage

An improved plow system would allow the rider to sit with one foot on each footpeg as opposed to side saddle (Fig. 1-5), raise the plow at least 2 in above the ground (enough to clear any obstacles) and deploy the plow to a maximum 8 in deep (A typical maximum plowing depth). These values were derived from conventional plowing practice.[4] It must be able to withstand oncoming forces of up to 600lbs [1] and downward forces up to 200lbs [1, 5].

A manually operated plow was considered. When stopping at the end of a row, the plow is buried in soil. The soil on top of the plow when buried 8 in deep and is estimated to weigh at least 30 lbs [Supplemental Information 8.2]. This number neglects any soil cohesion, which would require additional force to overcome. In a manually operated plow, the farmer would lift the 30-pound load over 130 times per acre [Supplemental Information 8.3]. This is an unreasonable expectation for the farmer. Because hydraulic capabilities were already added to support the 3pt, the

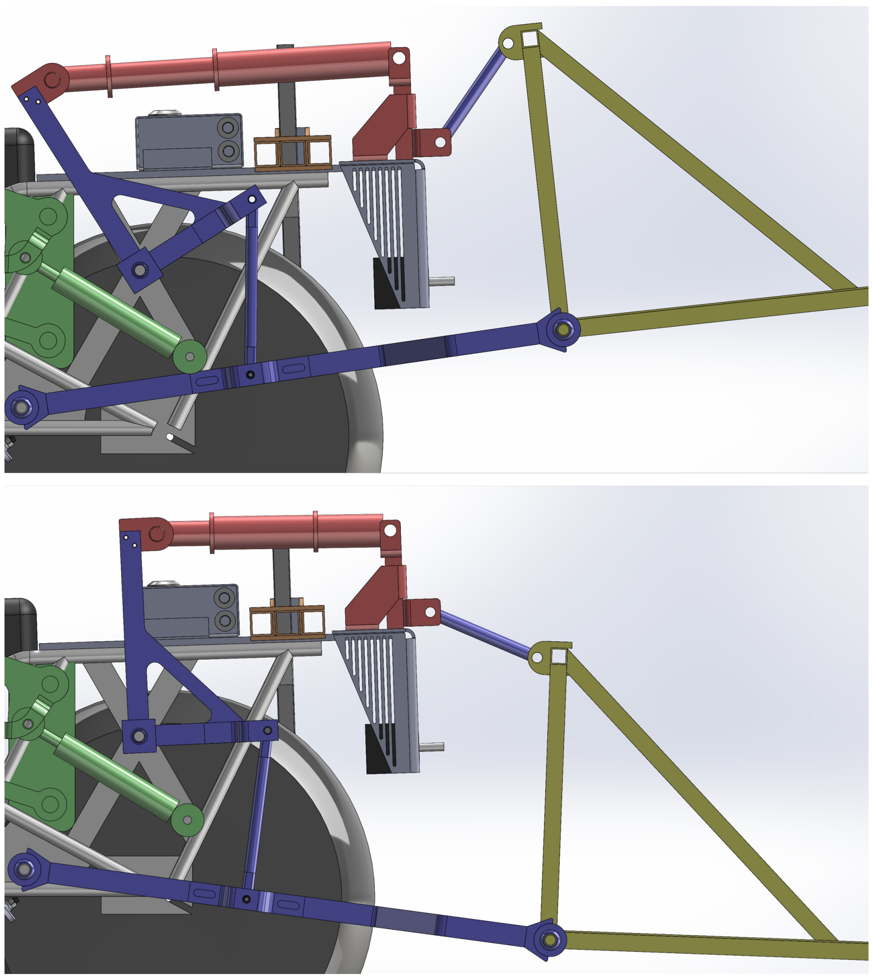

Figure 2-4: New Bullkey 3pt prototype in raised position (TOP) and lowered position (BOTTOM). An implement is seen in yellow, the hydraulic cylinder in red, and the linkage in blue.

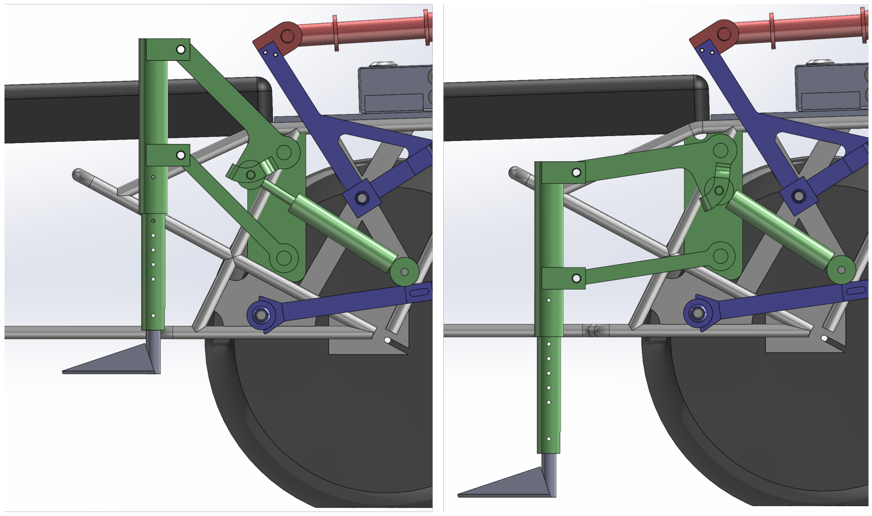

Figure 2-5: Hydraulically driven plow linkage prototype, raised (LEFT) and lowered (RIGHT).

plow was decided to be hydraulic as well.

Using the same process as described for the design of the 3pt linkage, a linkage for controlling to plow was synthesized. The geometry of a plow creates loads in three directions. a side-load equal to 25% of the draft force and a downward-load equal to 33% of the draft force should be expected [5]. Because dynamic loads from all directions are be expected, this design must be robust and free and long-term fatigue. The plow as designed is a 4-bar linkage driven by a Wolverine 1"x4" hydraulic cylinder (Prince Hydraulics, North Siux City, SD). While the actuation is hydraulic and discretely controllable, the plow is designed to be raised entirely or lowered entirely. The depth of the plow while deployed is adjusted by fixing a telescoping rod inside of a tube at a given position with a pin. The plow linkage is shown in Fig. 2-5. The assembly is made from cut sheet-stock and drilled tube and actuated by a small hydraulic cylinder [6].

2.5 Power Take-Off

A tractor with a PTO is a mobile source of rotational mechanical power which can be used to power any conceivable implement within the tractor's PTO output power specification. Vehicles which do not have a PTO have a significant functional disadvantage in the market compared to those that do. A Bullkey PTO would need to run at a minimum 540 RPM (the standard operating speed for agricultural PTO) and be capable of delivering at least 2hp (A common power requirement for many garden-sized implements) to a rear mounted implement.

Installing a PTO on the Bullkey's two-wheel, inline format presents a unique challenge. Figure 2-6 (LEFT) depicts a simplified diagram of a conventional tractor drive-train. A forward-mounted engine delivers power to the rear wheels via a spinning shaft, and gear box. The PTO spindle can be engaged or disengaged from the gear box via a clutch. Figure 2-6 (RIGHT) depicts the drive-train of the Rokon scout, which is significantly more complicated. A centrally mounted engine turns a drive belt which powers the input shaft of the vehicle's transmission. Power is transferred vertically through the vehicle inside a transfer case. At the top of the transfer case, a sprocket on the right side of the vehicle powers a chain to the rear wheel, causing it to turn. From the front of the transfer case, a universal shaft carries power underneath the seat and fuel tank to a bevel gear box above the front wheel. A chain delivers power from the bevel gear box to the front wheel.

In the Bullkey tractor, there is no main drive shaft to deliver power to a PTO. Even if there were, it could not be extended out the rear of the Bullkey (or any two-wheeler) because of interference with the rear wheel.

Instead of conventional, mechanical drive, the Bullkey PTO uses a Concentric brand 0.194 cu-in/rev hydraulic pump (Concentric AB, Worcestershire, UK), mounted in the rear of the vehicle (Fig. 2-7). Routing mechanical power to the rear of the vehicle would require a large number of spinning mechanical elements and several clutches. This system would be costly, inefficient, and represent a safety hazard. Hydraulic hose can be routed easily around the frame of the vehicle and delivers power with only small frictional losses. The hydraulic PTO is controlled by a 3 position, detented spool. It can be locked into either forward, reverse, or non-active position.

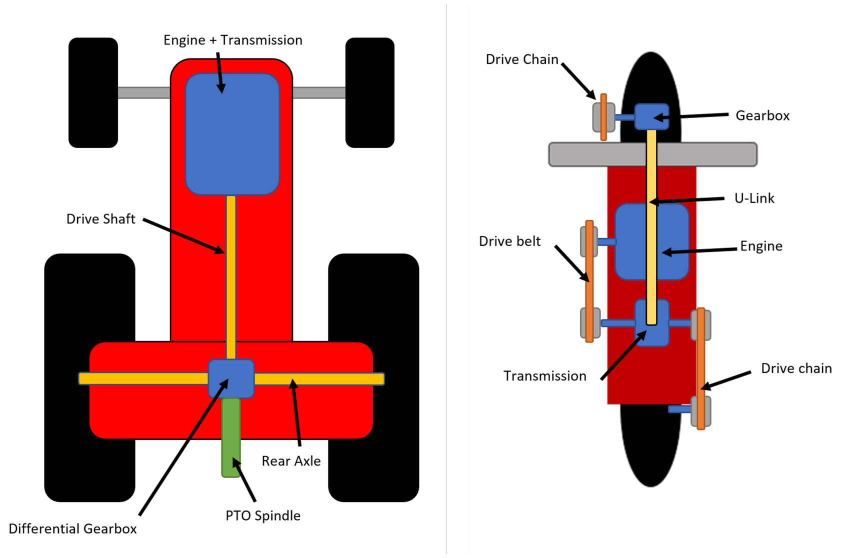

Figure 2-6: Stylized and simplified diagrams of the drivelines of a conventional tractor (LEFT) and the Rokon Scout (RIGHT).

Figure 2-7: The Bullkey PTO spindle connected a rear-mounted implement.

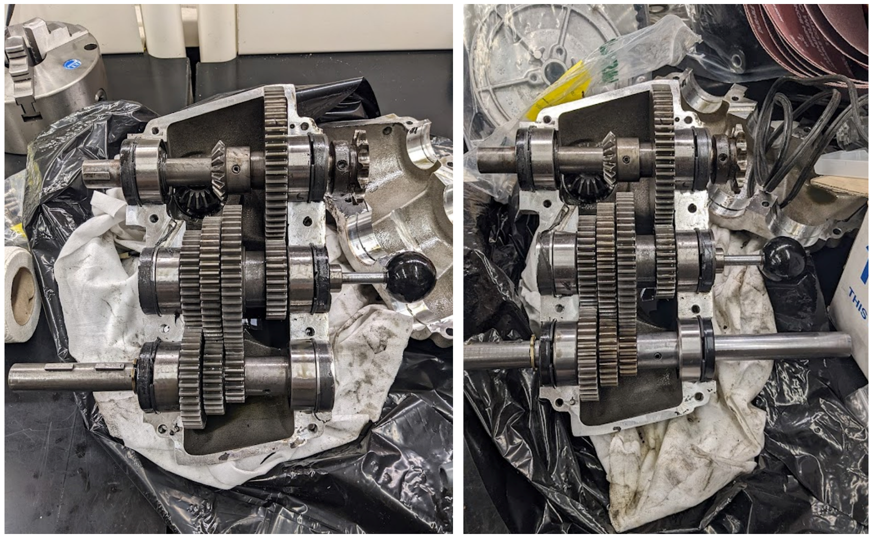

Figure 2-8: The original (LEFT) and modified (RIGHT) vehicle transmission

2.5.1 Hydraulics

Hydraulic actuators were implemented for powering the PTO, plow and 3pt based on their unique advantages in those applications. In addition, hydraulic components are safe and ubiquitous even in rural communities in India [7], which lends to the repairability of the product. Furthermore, by powering all components in a single hydraulic circuit, cost, complexity, and bulk are reduced.

To fulfill the functional requirements of the Plow, 3pt and PTO, the Hydraulic circuit must be capable of generating a 2 hp flow with a minimum pressure of 200 psi and minimum flow rate 1.2 gpm [Supplemental Information 8.4].

The Rokon transmission (Fig 2-8) was modified to extend the input shaft out through the right side of the case. Sprockets and chain connect this shaft to an adjacent hydraulic pump [8] bolted to a bracket which is welded to the frame. The pump draws fluid from a custom-built reservoir mounted behind the rider and pushes it to a 3-spool control valve mounted on the left fork of the front wheel. Each spool in this block controls one of the vehicle's 3 hydraulic functions (the plow, 3pt or PTO). The spool valve includes an over-pressure check valve, which set to release when pressure exceeds 1000 psi. Figure 2-9 depicts a schematic of the hydraulic circuit.

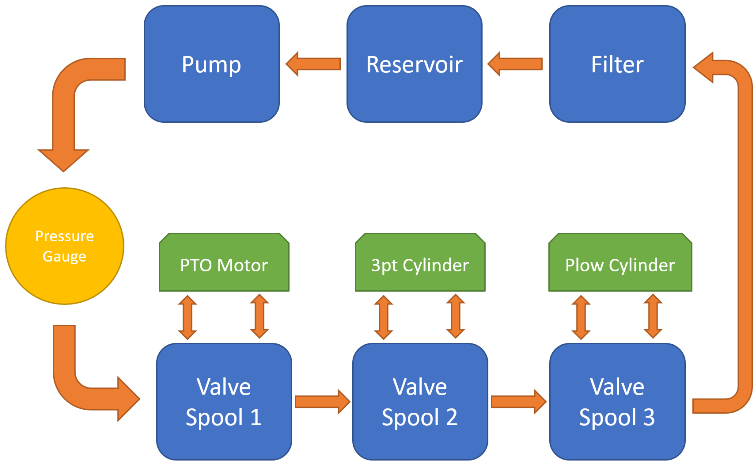

Figure 2-9: Schematic of Bullkey Hydraulic Circuit

2.6 Orchard Spraying

In 2021, India produced more than 10% of the world's total fresh fruit volume [9, 10]. Farmers were understandably insistent that the Bullkey be capable of spraying orchards. To service these requests, a chemical blower was designed. Blowers are common in agricultural applications for spraying orchards because propelling fluids to high heights requires tremendous power in pressurized-fluid spraying. As the droplets decrease in size, their surface-area-to-weight ratio becomes very large. This creates high drag forces relative to the droplet's inertial forces. A blower system can be used to turn this disadvantage in our favor by creating a high-speed air stream for droplets to ride on. Rather than the comparatively high drag forces causing droplets to fall still in stagnant air, the drag forces propel the droplet large distances. are propelled by fast moving air over great distances. An appropriate blower system would be able to propel fluid up to 5m vertically (the height that trees are most often pruned to in India [7, 11] at variable flow rate, but at least 2 ga/min [12].

The Bullkey electrical system is powered by a stator built into the engine which generates approximately 200 watts. Comparable market products are powered by 2 hp motors. Since Bullkey does not have the electrical capacity to drive a blower of this size, the blower is driven by the PTO. During tests of early prototypes, a gasoline-

Figure 2-10: Bullkey supports the blower and 15ga water tank via 3pt hitch. The PTO is connected to the blower via universal link.

powered blower and a 436 cfm flowrate was observed to atomize the fluid propel it up to 10 m vertically. A Dayton 6XWG9 high pressure blower (Dayton Electric Company, Dayton, TX) with was selected (Fig). The blower fan was connected to the PTO via a telescoping slip shaft with universal joints (Maedler, Stuttgart). Fluid is fed into the mouth by a Northstar NSQ 12V On-Demand Sprayer Pump (Northern Tool, Burnsville, MN).

2.7 Vertical Sprayer

Farmers in group discussions indicated that Bullkey would be useful for driving between rows of tall crops to spray chemicals. This is possible due to the vehicle's uniquely narrow footprint. Conventional crop sprayers are expensive, specialized machines which are not viable on the smallholder scale [7]. Instead, laborers perform the task with knapsack sprayers. This practice is known to be resource-inefficient and a health hazard for workers [7, 13].

A solution to this problem would spray fluid to both sides of the vehicle, covering the full height of a crop on both sides as the operator drives down the row. The

Figure 2-11: Prototype vertical sprayer mounted on the Bullkey tractor.

tallest and most common crops grown in India are corn and maize, which mature at an average height of 7 feet in India and are often planted in rows about 30-40 inches apart [7, 11]. Accordingly, the Vertical Sprayer should be able to spray a crop which is up to 7 feet tall and 20 inches away. According to herbicide manufacturer recommendation and assuming a travel speed of 3 ft per second, the sprayer should dispense approx. 1 ga./min [Supplemental Information 8.1]. The volume flow rate should be adjustable to accommodate farmer preference.

The newly designed sprayer frame measures 4.5 feet tall and includes three sets of opposite-facing, wide-angle sprayer tips (Fig. 2-11). Fluid is drawn from a tank by a 12v start/stop pump [14] powered by the vehicle's stator and propelled up the sprayer and out the tips on either side. The sprayer can be turned on and off via a toggle switch mounted under the tractor's left handlebar.

2.8 Ballast Racks

To address concerns related to ballast racks, new front and rear ballast racks were designed. The front rack is connected rigidly to the frame. The rear rack connects to the 3pt. Both can be seen in Figure 2-12. These racks are designed to accept athletic

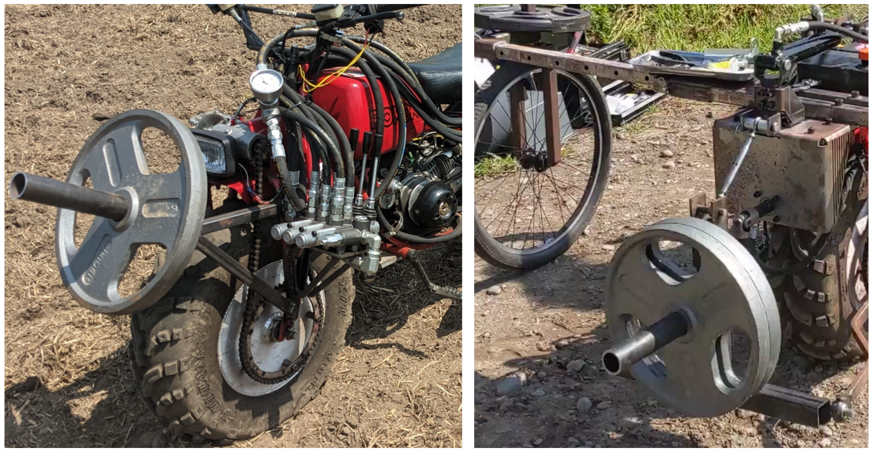

Figure 2-12: New front and rear weight racks prevent tripping while walking around the vehicle.

weight-lifting plates conforming to the Olympic standard. These plates are globally ubiquitous for strength training. Costs related to shipping heavy OEM ballast weights for typical tractors are very high. By using weights which can be locally sourced and sell in much larger volume, cost and accessibility are promoted.

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Chapter 3

Methods and Results

3.1 Physical Testing

The prototype vehicle was tested at Clark Farm in Carlisle, Massachusetts. A series of tests were used to verify that each of the upgrades performed as designed. Throughout testing the authors consulted with the farm manager and farm workers about the performance of the vehicle. Each operation was performed by at least three and up to five different operators to compare perceived comfort and performance.

3.1.1 3 Point Hitch and Hydraulic Pressure Testing

Weight and pressure testing were performed to verify that the load-bearing capacity of the 3pt meets the functional requirement of 300 lbs. The rear ballast rack was fitted to the 3-point hitch and weights were added incrementally. With each increment, the hydraulic 3pt was raised up and down to verify ability to lift that weight. A pressure gauge [1] with 50 psi resolution in the hydraulic circuit between the pump and the spool valve (Fig. 14) was used to read out pressure during lifting and at the limits of cylinder travel. Activating the cylinder while it is at the limits of travel simulates a “maximum load” scenario where pressure is applied to the cylinder’s dividing wall while it can no longer move. The pressure in the circuit has also be measured in a "no-load" state while the pump is running and the PTO, 3pt and Plow are not in use.

This is important for quantifying the latent power drain in the engine caused by losses in the hydraulic circuit. The operator's weight during this test was approximately 120 lbs.

The new 3pt demonstrated capacity for lifting more than 300 lbs. The 3pt as designed has a weight capacity far more than 300lbs but must be limited because the rated weight capacity of the Rokon base vehicle is only 600lbs, inclusive of the rider.

While idling and powering no implements, the hydraulic circuit does not produce measurable losses. Pumping fluid through the circuit at an idle flow rate was calculated to require less than 20 psi. Indeed, this idle pressure was not measurable with the installed pressure gauge, which has a resolution of 50 psi. When either the plow or 3pt cylinder were driven to the limits of their travel, the system was observed to produce up to 2200 psi. As the system is only rated for 2500 psi, further pressure was not tested, and the overpressure safety valve was adjusted to 1000 psi from there forward.

3.1.2 Blower and PTO Testing

The blower module and tank were mounted to a platform supported by the 3pt. The face of the blower was positioned to create an airstream at 45 degrees upwards from the ground to the side of the vehicle. Fluid was pumped into the blower at 1ga/min while the PTO drove the blower fan at approx. 1200rpm. This test was performed stationary, stationary while adjusting the height of the 3pt, and while driving at about 1m/s with the 3pt height fixed. Wind speed as measured directly at the outlet with an anemometer. The distance the fluid traveled vertically and horizontally were measured with a tape measure.

PTO Shaft RPM was measured by laser tachometer. Fluid displacement for one revolution of the PTO shaft is known, so PTO Horsepower can be calculated from shaft RPM and fluid circuit pressure to validate the functional requirement.

The new blower was observed to propel fluid approximately 15 ft from the vehicle and approximately 10 ft high. The blower could be operated at a maximum speed of 1200 RPM and produced roughly 600 psi of pressure in the hydraulic circuit. During stationary testing, air speed was measured at 15 m/s.

During stationary testing, the blower produced a flow velocity of 15 m/s, or roughly 400 cfm. To increase flow speed, a reducing flange was mounted to the outlet of the blower. This effort was unsuccessful, as the blower does not generate sufficient static pressure to maintain volume flow rate through the reducer. The blower was directly driven by the PTO at 1200 rpm and generated just 600 psi of load on the hydraulic system - less than half of the observed maximum pressure of the system. 600 pis and 1200 rpm equate to just .35 hp., while the vehicle's engine can produce 7 hp. In other words, the PTO can supply much more torque at the same RPM than the blower could demand at 1200 rpm. If the blower fan were geared up, the PTO could easily supply the needed power to drive a much stronger airstream. Additionally, the blower orientation can only be changed in 45-degree increments. With more fine control over the direction of the blower and airstream, and a higher-speed blower, spraying of even taller trees/crops is possible.

3.1.3 Vertical Sprayer Testing

The Vertical Sprayer system was connected to a platform supported by the 3pt and the sprayer pump connected to the battery. Flow was adjusted to around 1ga/min. The sprayer was first tested stationary to measure the height and width of spray. Then, the sprayer was tested on a tall asparagus crop to examine coverage. The local farm for testing did not have adjacent rows of tall crops suitable for driving between rows, so the vehicle was driven alongside one row of crops at about 1m/s. The height and width of the spray was measured with a tape measure in order to validate functional requirements for crop coverage.

The vertical sprayer assembly sprays in a plane projected behind and to the side of the operator approx. 8 feet high and 30 inches from the side of the vehicle. Two operators tested the sprayer and did not feel the spray touch them during operation, and crop coverage was judged to be adequate. Because the flow rate is adjustable, a user may modulate flow rate and/or vehicle speed to control crop coverage. The 1 gal./min flow rate calculated from manufacturer recommendations was achieved.

3.1.4 Plow Testing

If the plow design is successful, it will bury itself automatically when in float mode. It must also be able to lift itself out of the soil, even if buried. The plow should also not fail structurally under plowing loads.

To test the plow, the plow was adjusted to have a maximum depth of 8 inches. The operator approached the soil bed and set the plow to “float,” dropping the plow to the ground but applying no force against it. The vehicle was driven forwards at 1 m/s causing the plow to bury itself due to soil forces acting on its geometry. The operator proceeded down the bed at 1 m/s, pausing every 30 feet to raise the implement out of the bed to test how the plow lifts from the soil. Then, the plow was set to “float” again before the vehicle began moving forward. Several operators also plowed a full row to gauge comfort and control of the vehicle.

During plowing, once float was activated, the plow would bury itself to maximum depth without operator intervention. Five operators felt the vehicle was comfortable to operate and control. With 45 lbs. of load at the outrigger wheel, the vehicle was easy to keep upright without operator effort. The vehicle was able to plow successfully up to 8 inches of depth. The new plow linkage showed no signs of deformation or damage during or after plowing. After plowing, the upgraded linkage easily lifted the buried plow through the soil to a raised position. Five operators agreed that the vehicle is comfortable and easy to control while plowing, and the controls are comfortably within reach and easy to manipulate.

3.1.5 Outrigger Wheel Testing

OW testing consisted of observing the stability it contributes to vehicle operation and its ability to support weight across its length. While testing stabilization, an operator performed a series of 180 degree turns at approximately 2 m/s, and weight was added as necessary to control the roll of the vehicle. The OW was also employed while performing all other tests to gauge stability during off-road and farming operation. To test weight capacity, weight was incrementally added at the mid-point of the fully deployed length of the OW until the designed weight capacity was achieved to test whether the OW can support the required weight across its length.

The OW was observed to support the specified weight of 300lbs statically. It was also shown to support 60lbs of ballast loaded directly to the wheel to resist tipping, however four different operators agreed that 45 lbs was sufficient. The same four operators also felt that adjusting the length of the OW was an easy and convenient process.

3.2 Methods and Results: Stakeholder Interviews

3.2.1 Local Interviews

Workers from Clark Farm (including one worker with experience on small farms in the United States and one worker with experience on small farms in The Philippines) were invited to test the Bullkey tractor. Following their testing experience, authors held an interview to inquire about their experience with and perception of the prototype vehicle. Questions asked are found in Supplemental Information 8.5.

The worker from The Philippines comes from a small farm that raises buffalo for milk, meat, and labor. This worker said they found it easy and familiar to ride and that the controls felt comfortable. They thought it would be easy for others to learn, too, as most people from their home country know how to ride a motorcycle already. The worker insisted that the tractor would do well on their family's farm in The Philippines since their farm is quite small and tractors are too expensive. The worker from the united states also indicated that the vehicle would have value on their small farm.

The worker from the United States has the most experience with tractors between 30 and 60 hp. This worker expressed surprise that the Bullkey was capable of performing plowing operations despite its size. The worker indicated that it would be a valuable addition even to a small farm in the united states for secondary tillage, planting and crop maintenance operations.

3.2.2 Interviews in India

For reading on planned interviews with stakeholders in India, read chapter 4, section 2 of this thesis.

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Chapter 4

Discussion and Limitations

4.1 Discussion

The need for affordable and effective farm machinery was identified through interviews with farmers, machinery salespeople, and other stakeholders in India. While products and services are available to address this market shortcoming, interviews and discussions also indicated that end users find these solutions lacking. The development of the original Bullkey prototype tractor was a considerable step towards a better solution. In group discussions, farmers expressed certain functional expectations for a tractor that the original prototype could not fulfil. These included compatibility with implements they already own via 3pt and PTO, and the ability to tend a wider variety of crops with an adjustable OW. Farmers also identified new processes that the Bullkey platform could perform that conventional tractors or draft animals could not, like driving between rows of tall crops to spray the sides of the crop. Lastly, ergonomic flaws were identified as obstacles to adoption. These include requiring the operator to sit side saddle and raise and lower the plow through a tedious cranking motion. These technology gaps motivate further development of the Bullkey Tractor.

A series of upgrades to the Bullkey tractor were proposed to fill these technology gaps. These upgrades included the implementation of hydraulic power to drive a novel, miniaturized 3pt system which conforms to an international standard, making it compatible with existing implements. The hydraulic power also drives a PTO (which allows user to power an external implements) and a linkage which raises and lowers a plow into the soil (reducing the tedium of manual operation). The new plow linkage is also highly compact, and no longer interferes with the rider's ability to straddle the vehicle conventionally. The redesigned OW is easily adjustable, and can be stored on the vehicle for transit. A new, tall-crop spraying system increases the efficiency and speed of chemical application to tall crops and reduces worker exposure to the same chemicals. A chemical blower implement allows Bullkey to serve orchards and demonstrates the capabilities of the PTO.

This research contributes to the academic community by demonstrating how careful consideration of the resources and manufacturing processes available to end users and their communities can help foster adoption of an eventual product. During the design process, special care was taken to keep cost, weight, and bulk very low. By emphasizing parts that are locally manufacturable, designers can reduce end user fears about long-term repairability and the cost of maintenance. The motorcycle layout of the vehicle makes it accessible to new operators and familiar to motorcycle mechanics, especially in regions where two-wheeler riders far outnumber car drivers. In this sense, the vehicle is robust not only in its durability, but in its resilience to disruptions in supply chains or other industrial infrastructure.

The resulting product is an upgraded Bullkey prototype with wide-ranging impact in resource-constrained markets. In addition to past work which demonstrates that an inline-drive, two-wheel-drive vehicle produces sufficient draft force to replace draft animals, this work demonstrates that such a vehicle can also operate modern implements. In this regard, the Bullkey tractor combines the benefits of draft animals and low-power machinery. If disseminated and commercialized, the Bullkey tractor will be a valuable source of agricultural power with a low upfront cost relative to conventional tractors and a low annual cost relative to draft animals. The careful combination of core machine design principles and ethnographic data produces a marriage of functional offerings which constitutes an important design innovation. This knowledge should be adapted to help ensure acceptance of other novel products in resource-constrained markets. This technology shines in agriculture and should also be considered for applications in disaster relief, defense, construction and landscaping.

4.2 Limitations

Due to the hydraulic pumps mounting to the input of the vehicle transmission, the hydraulic implements can be actuated while the vehicle is in neutral, or while the vehicle is moving. However, if the vehicle is in gear and stopped, the pump will not run. This is because while in gear, the transmission input is connected to the wheels of the vehicle. The following example describes how this impacts workflow:

While plowing, the vehicle will begin in gear and stationery. The operator lowers the plow using the float function. (Float does not require that the pump is running, as it simply relieves pressure in hydraulic cylinder.) The plow lowers to the ground and the operator accelerates towards the end of the row. As the operator reaches the end of the row, they may either A) raise the plow as they approach or pass the end of the row, or B) stop the vehicle, switch to neutral, raise the plow, switch back to gear, and proceed. The farmer may not simply stop the vehicle while in gear and raise the plow.

If the hydraulic pump was instead connected to the engine output shaft, the hydraulic pump would be powered whether the vehicle was in neutral or drive, regardless of the state of motion. This implementation is possible with heavy modifications to the frame of the vehicle.

A low-displacement hydraulic pump was selected to reduce the acceleration of the plow or loads on the 3pt hitch. However, output power of the hydraulic system could be increased with higher flow rate, so a larger-displacement pump should be considered.

Many design decisions were made with deference to the geometry of the base vehicle. While the frame was heavily modified to accommodate attachment points for the various upgrades, the implementation could be optimized with a custom base vehicle. For example, steel tubing could replace many of the long, hydraulic hoses which run the length of the vehicle. This would reduce weight, cost, and bulk by eliminating large, insulated hoses.

In future work, group discussions and semi-structured interviews will be held with farmers in India to validate that the upgraded Bullkey prototype is valuable to and likely to be adopted by smallholder farmers. This research will be completed in partnership with the SM Sehgal Foundation. During group discussions, farmers will be shown a video compilation of the upgraded Bullkey prototype in operation. This video will cover functionality of the original prototype and highlight the new functionality of the upgraded prototype, including PTO operation, hydraulics, new sprayers and adjustable OW. After viewing the video and listening to a description of the work from a representative of the SM Sehgal Foundation, stakeholders will complete a paper survey in which they indicate how they perceived the vehicle and whether they believe they or their community are likely to adopt the technology. This survey will be approved by the MIT Committee on the Use of Human Experimental Subjects.

Chapter 5

Conclusions

This paper discussed a market gap which can be filled by a low-cost, ultra-compact tractor capable of performing daily farming tasks. In discussing various alternative solutions (including the initial Bullkey prototype) and their shortcomings, the functional requirements of a more suitable solution are formulated. The inception, design, implementation and testing of several upgrades to the Bullkey platform discussed in this work address these market and technology gaps. These upgrades included the implementation of hydraulic power, the design of highly-compact mechanical linkages for plowing and interfacing with three-point-hitch implements, addition of a power-take-off, an adjustable, storable, balancing outrigger arm and two new chemical spraying apparatuses.

The design of each upgrade was discussed in detail. Common amongst each upgrade are the special efforts made to reduce weight and consequently cost. Stakeholders from three regions of India were regularly consulted and special consideration was given to the resources and manufacturing capabilities of the stakeholder's communities when designing the upgrades.

The resulting upgrades were implemented and tested at a small farm in Massachusetts, and demonstrated fulfillment of functional requirements specified in this paper. Workers at the farm test site from the US and the Philippines tried the vehicle and felt it would meet the needs of their own small farms and be valuable to farmers there. The upgraded prototype, its performance, and photos of videos from field testing were then discussed in open discussion with farmers in India. These farmers felt that a Bullkey tractor would be a valuable addition to their farm and would reduce drudgery and labor costs.

The upgraded Bullkey prototype could have considerable impact on farmer livelihood in resource-constrained communities. Being projected to cost only slightly more than a bullock pair, it represents a tremendous value proposition for the adopting farmer in its functionality and versatility.

Chapter 6

Supplemental Information

6.1 Chemical Flowrate

Roundup Brand recommendation: 40 fl. oz. / acre

Roundup Brand recommendation: 2 fl. oz. / gallon

Gallons required to spray one acre: 20 gallons

Square feet in one acre: 43560

Side length of a square acre: 208 feet

Crop row spacing: 2.5 feet

rows/acre: 70

Time to spray 1 row while riding 3 ft/s: 23s

Time to spray all rows: 26 min

Flow rate to empty tank on one acre: 0.75 ga./min

6.2 Force Required to Raise Plow

Density of Indian black soil: 0.066 lbs / in^3

Surface area of plow: 32 in^2

depth of plow: 8 in

Weight of soil directly above plow surface: 17lbs

Weight of plow: 13lbs

Total force to lift plow and soil: 30 lbs

6.3 Passes Required to Plow One Acre

Square feet in one acre: 43560

Side length of a square acre: 208 feet

Width of furrow: 1.5 feet/18in Passes to plow one acre: 139

6.4 Hydraulic Flow Parameters

Cylinder bore diameter: 1.5 in

Dividing wall surface area: 1.76 in^2

Load applied to hydraulic cylinder when raising max load: 150lbs

Psi required to generate force: 85 psi

Apply factor of safety 2: 200 psi.

Cylinder bore diameter: 1.5 in

Dividing wall surface area: 1.76 in^2

Stroke Length: 6in

Cylinder Volume: 14 in^3

Cylinder Volume = 0.07 ga

Desire to fully extend cylinder in 4 seconds

Flowrate required = 1.16 ga/min

6.5 Discussion Topics During Semi Structured Interviews

"What did you think of the vehicle?"

"Do you think the tractor would be valuable on your farm?

"Do you think the tractor would be easy for members of your community to use?"

"Do you think it would be easy to find replacement parts for the tractor in your community?"

"If you needed a part that you couldn't buy, do you think you or someone you know would be able to make a replacement?"

"If the tractor became damaged, do you think you or someone you know would be able to fix it?"

"How much would you be willing to pay for this tractor?"

"What sorts of operations would you use this tractor for?"

"Do you have farming needs that this vehicle does not satisfy?"