Proceedings of the ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference
IDETC/CIE 2017
August 6-9, 2017, Cleveland, Ohio, USA

DETC2017-68132

DESIGN OF AN INTEGRATED COTTON PICKING SYSTEM FOR SMALL-SCALE INDIAN AGRICULTURE

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ABSTRACT

India, the world's largest producer of cotton, contains more than 4 million cotton farms that are less than 5 acres. These farms are incapable of large-scale mechanization due to small farm size and irregular farm shape. A previous team developed a handheld, roller-based picking device that demonstrated increased performance over similar products. However, a significant improvement in productivity requires increasing picking speed through mechanization as well as increasing worker cotton carrying capacity. We present a system that utilizes the roller-based picking device in tandem with a compressive storage bag and an efficient carrier. Through modeling and initial testing, the system demonstrates a two times (2X) improvement in worker productivity over current methods. This paper characterizes the cotton picking process, details the modules of the integrated system, and suggests further procedural improvements for greater increases in worker productivity.

1. INTRODUCTION

The goal of this paper is to describe limitations in the manual cotton-picking process and suggest improvement opportunities. Opportunities include process modifications and introduction of novel tools.

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1.1 Background and Motivation

Two thirds of the global cotton production comes from developing countries. During the last five decades, global cotton production grew at an annual average rate of 1.8% to reach 27 million metric tons in 2013 from 10 million metric tons in 1960 [1,2,3]. Most of this growth came from India and China, which tripled and doubled their production within this period. As of 2016, India is the largest producer of cotton in the world with a production of 5.89 metric tons [3]. **Table 1** shows top cotton producing countries and their annual production every other year over the last 6 years. India's cotton production was majorly aided by the introduction of genetically modified Bt Cotton that improved yield while reducing cultivation costs and use of insecticides.

	2012/2013	2014/2015	2016/2017
India	6.22	6.44	5.89
China	7.64	6.55	4.58
USA	3.77	3.56	3.60
Pakistan	2.03	2.31	1.81
Brazil	1.31	1.53	1.42
Australia	1.00	0.50	0.98
Uzbekistan	1.00	0.85	0.81
Rest of the World	4.06	4.28	3.64
World Total	27.03	26.01	22.73

Table 1: World Cotton Production 2013 - 2016 [3]. Measured in millions of metric tons.

Cotton farming in India, however, is highly dependent on manual labor with minimal automation. While considerable automation has been brought into practice on the crop cultivation front through machinery for tilling, plowing, sowing etc., very little has been done to automate the cotton harvesting process which is referred to as cotton picking. Developed countries use standard cotton picker machines that automate the cotton harvesting process on large scale farms to reduce time and increase efficiency. These cotton picker machines are not applicable in the Indian context for several reasons:

1. India has 5.8 million cotton farmers with an average farm size of 4 acres (ranging from 2 – 10 acres) and no standard geometry [4,5]. These farms do not have the economies of scale to justify large cotton picker machines.
2. Cotton plants in India vary in height. The cotton flower can be at a height of 6 inches to 6 feet from the ground. Cotton plants in large US industrial farms have a smaller height range that fall within the specifications of the cotton picker machines [6].
3. Cotton plantations in India are non-standard in row-to-row distance and plant-to-plant distances. Row-to-row distances can vary from 60 - 90 cm whereas plant-to-plant distances vary from 25 - 70 cm [6]. The industrial solutions that exist today are not designed to cater to such non-standard fields.
4. Using the automated cotton picker for the harvesting process necessitates damaging the crop to extract the cotton bloom. Indian Bt Cotton plants are harvested four to five times in a season, so using an automated large cotton picker becomes infeasible [7].
5. The market for large farm equipment in India generally works on the leasing model [6]. Some people in a village own farming equipment which is leased by farmers as needed. With cotton pickers being specific to the industry, equipment owners do not look at it as a high return on asset (ROA) investment.

The above constraints suggest a vast untapped market for mechanized cotton pickers specifically designed for these farms. Mechanization could have a two-fold benefit of increasing the productivity of human cotton pickers while reducing the drudgery of manual cotton picking.

With automated cotton picker machines not suitable for most small-scale Indian cotton farmers, a large Indian OEM agricultural equipment company that was partner for this project identified improving the productivity of human cotton pickers (HCP) through mechanization as an opportunity to increase efficiency for millions of farmers. This company understood that for significant impact, the cotton picking rate will have to be improved to three times (3X) the current manual picking rate. At a macro level, the manual cotton picking process as performed by the HCP consists of three main tasks – plucking, carrying and collecting. To achieve the target of 3X picking rate, the design solution may need to improve the capabilities of the HCP in more than one task.

1.2 Value Chain Analysis

In order to design a solution that positively impacts the entire ecosystem, it is important to gain insights into the stakeholders engaged in / affected by the process.

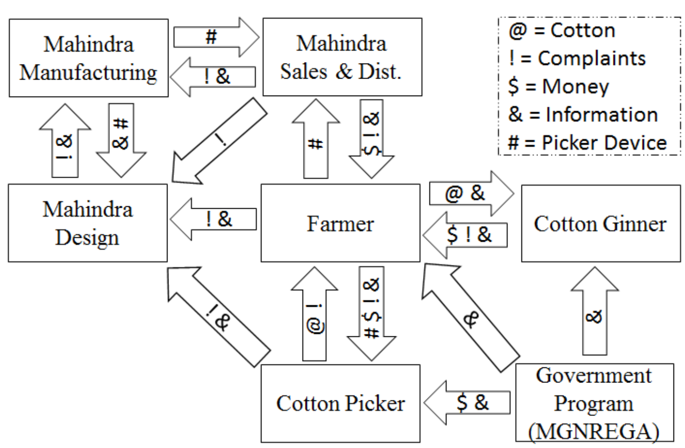

Figure 1: Value chain analysis for cotton picking process

Figure 1 shows the relationships between these key stakeholders. These relationships help us understand that any design solution should improve the HCP's working condition while providing financial gain to the farmer and maintaining or improving the current quality standards. Below is a brief description of the key aspects of the value chain analysis.

Our agricultural industry partner highlighted that a key driver of market opportunity is the increasing difficulty of finding labor for cotton harvesting. The cotton harvesting period in India lasts from September to January [8]. During this season, an average cotton farm undergoes four to five harvesting cycles. HCPs are employed separately for each bloom. Due to the seasonal nature of the work, most HCPs are rural women whose main roles are managing their homes and families. Over the last decade, an increasingly large number of the Indian rural population has migrated to cities. This has led to an overall low supply of labor for farm activities in rural India. Additionally, a current employment scheme known as the Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) entitles at least 100 days of guaranteed wage employment in a financial year to every household whose adult members volunteer to do unskilled manual work. This act sets the minimum price for unskilled labor at INR 122 – INR 190 (~$2 – $3) per workday [9]. The employment provided under MGNREGA is for infrastructure development activities undertaken by the state or local government. One of the key failures of this policy is that its success is driven by the supply of jobs rather than the demand for work. With guaranteed wages for 100 days a year, a lot of the available workforce prefer to apply for this guaranteed employment scheme and get minimum wage without working when there is a low supply of government infrastructure jobs. As a result, it increasingly difficult for farmers to find the required labor to harvest their cotton field and pay an attractive premium over the minimum wage.

Since the cotton harvesting process is unique to the industry, our agricultural industry partner foresees that a designed solution to tackle the complexity of the process will possibly be unique to cotton. This might mean that the solution will have to be bought and owned by cotton farmers themselves. As a result, the existing renting model prevalent for all common industrial machinery will not be a viable business model. For our agricultural industry partner, the customer for any mechanization of cotton harvesting is the farmer. The buying power of the farmer is a key input for the design solution.

While the farmer is the expected buyer of the designed solution, large scale adoption of the solution would be possible only if the end user (the HCP) finds the new solution easier to use compared to their current manual picking process. Since our target is to increase the rate of cotton picking by 3X, our key user for the design inputs is the HCP. The average HCP is a rural Indian woman with a height of 5 ft. This will define spatial and energy / power-related design constraints. A key social constraint is that the standard attire of a rural Indian woman is a saree consisting of a drape varying from five to nine yards (4.5 metres to 8 metres) in length and two to four feet (60 cm to 1.20 m) in breadth that is typically wrapped around the waist, with one end draped over the shoulder, baring the midriff.

Another key insight is that the output of the process is harvested raw cotton which is bought by ginners. The value chain beyond the farm is an organized industry dependent on the input provided by farmers. Hence the quality expectations for raw cotton will be defined by the ginners. It is safe to assume that the current quality of cotton picked by the manual method is the minimum quality required for cotton output by the proposed design.

1.3 Current Cotton Harvesting Process

While the cotton picking process is non standard and completely manual, the current process can be divided into four stages - plucking, stuffing, intermediate storage, and central collection. Below is a brief description of these tasks.

1. Plucking: This task consists of grabbing a cotton bloom, aligning it with one hand, and using the other hand to pluck the cotton bud.
2. Stuffing: This is the action of storing the cotton on the HCP. A common method of carrying cotton is with a saree--the HCP creates a pouch using the draped saree and stuffs cotton in it. However, different parts of the country have different methods of carrying cotton such as sling bags, baskets, etc.
3. Intermediate storage: This step occurs when the HCP decides to create a small storage area in the middle of the field close to the area they are responsible for harvesting. The HCPs move back and forth between the field and this intermediate storage to deposit cotton. This step generally occurs in larger sized fields.
4. Central collection: During the course of the day, the HCPs frequently visit a central location on one end of the farm to deposit their harvested cotton. This central location generally has a large open tarp on which all the cotton is collected. The HCPs have to go back-and-forth between the field and central collection several times a day.

It takes an average of 30 work days to harvest one acre of cotton. However, due to the non-standard nature of the work, there is a huge variation around this average. We identified the intermediate and central collection steps as non-value added activities since they do not directly contribute to harvesting cotton. Data analysis of the time spent in these four steps shows that an average HCP spends 75% - 85% of their time in the intermediate storage and central collection parts of the process whereas only 15 - 25% of the time is spent on the actual harvesting activity of plucking the cotton buds [6]. **Figure 2** displays this time breakdown. Based on this, the productivity of a HCP can be increased in two ways: 1) increase the speed of plucking cotton and/or 2) decrease the time spent by the HCP on intermediate and central storage activities.

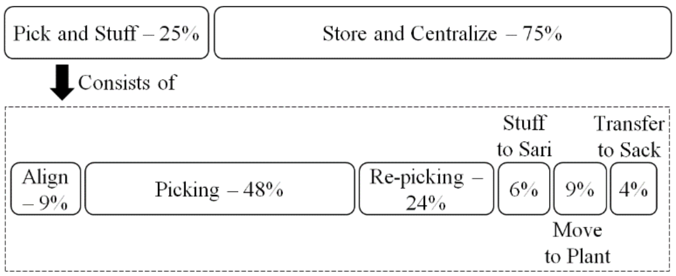

Figure 2. Time breakdown of cotton harvesting process

At an individual farm level, a farmer can approach this problem by optimizing operations through behavioral and process changes. Behavioral changes can be especially challenging to implement since these are deeply rooted in traditional practices. Moreover, these solutions cannot be standardized and applied across the country due to variations in socioeconomic conditions, farm shape, and farm size.

1.4 Existing Solutions and Limitations

The developing world market has several handheld cotton picking devices that claim to improve the cotton picking process under the previously defined conditions. These available devices can be classified into three main categories: front roller guns, cotton vacuums, or a combination of both. Prior teams and agricultural industry partner have conducted several bench level tests on these pickers and have found them to have the below key disadvantages.

1. Most handheld cotton pickers cannot consistently outperform purely manual cotton picking. Performance is measured in terms of kilograms of cotton collected per day per cotton picker.
2. The cotton collected using these handheld devices has higher trash content (e.g. leaves, branch fragments, dirt etc.) than manual picking.
3. Some of the handheld devices have the tendency to destroy crops, which is not conducive to Indian conditions where farmers depend on the crops to bloom five times in a given season.
4. Products require multiple attempts to achieve full cotton extraction from the buds. This increases the time spent on each cotton bud significantly.

1.5 Previous Work

One of the key achievements from the work of previous teams is a design concept aimed at automating the plucking of cotton balls from the cotton plants. The concept uses two rollers with frictional properties rotating in opposite directions via a DC motor drive. **Figure 3** represents a schematic of this concept.

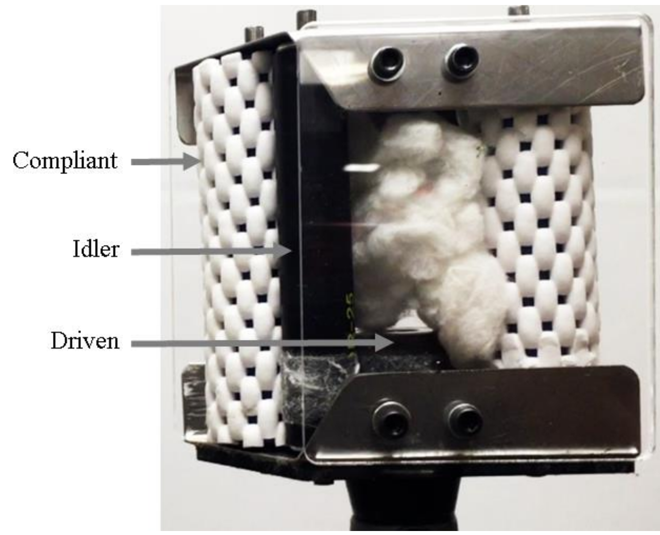

Figure 3: Roller-based cotton plucking mechanism

The key engineering parameters of the design are the roller dimensions (length and radius), the friction coefficient of the rollers, and the minimum and maximum gap between the rollers. The prototype concept was found to be successful in picking cotton balls from plants without damaging the seeds while capturing minimal trash and causing little or no plant damage. Test results showed an improvement in plucking rate of 51% [10]. This directly translates into a productivity improvement of 25% for a square-shaped four acre field.

Our agricultural industry partner accepted this design concept as a feasible method of plucking cotton from plants. The design team at our agricultural industry partner will work on the key engineering parameters to come up with the most optimum values to realize the highest productivity improvement with the least energy inputs. As an extension to the concept, it is important to identify a means of collecting and transporting the cotton that was plucked by the device to capitalize upon the advantage of the faster plucking rate.

This paper focuses on building upon this improved method of plucking cotton from the plant and assesses solutions for decreasing the time spent by HCPs in intermediate storage and central collection.

1.6 Design Requirements

The overall product design requirements for an automated cotton picker device for HCPs were defined previously as follow [10].

1. Increase output of a human cotton picker by 3X
2. Retain less than 2% trash within picked cotton
3. Cost INR 7000 (~$100 or less)
4. Reach between 0.3 m to 1.8 m in height
5. Hand device must weigh under 0.5 kg
6. Duty cycle of 2 days or more (applicable in case of external power source requirement)

With these overarching design requirements remaining the same, focusing on capturing and transporting cotton leads to specific requirements in these areas.

1. Increase carrying capacity of cotton picker by minimum 2 times
2. In case of a bag, it must be removable in less than three seconds
3. The bag must be replaceable in less than 15 seconds
4. Bag must be able to capture >99.5% of all plucked cotton
5. Decrease the frequency of back and forth trips for collecting cotton in central location by 50% minimum
6. Due to the non-standard nature of the farms, any solution developed should be modular in nature and easily scalable for different farm sizes and shapes.

2. A COMPRESSION-BASED SOLUTION

Several factors influence a farm's cotton production rate. The main factors are picking and aligning rate (r_p in kg/hr), carrying capacity per worker (C in kg), and consolidation time or time spent transporting cotton from picking site to storage site (t_c in hr). In a model developed by [11], the relation between these factors and cotton production rate can be described as:

$$P = T \; \frac{C\, r_p}{C + t_c\, r_p} \qquad \textbf{(1)}$$

where T is the time spent picking (hr). To potentially attain a theoretical 3X increase in cotton production rate, it is crucial to increase not only picking and alignment rate, but also carrying capacity per worker while simultaneously decreasing consolidation time. For sensitivity to improvements in discrete tasks, please refer to Figure 2.

We consider a strategy to increase carrying capacity per worker and reduce overall consolidation time by requiring fewer trips to unload cotton. Our concept relies on compressing cotton with a modular storage unit to form mini cotton bales; the unit can be attached to a cotton picker, and catches loose cotton as it is ejected by the picker.

Compressing cotton offers several advantages within the constraints present in India's cotton harvesting process. Carrying capacity is currently volume-limited, rather than mass-limited [12]. The huge variation in cotton plant distribution causes navigation through the field to be difficult with unwieldy volumes or shapes. Compression increases the mass of cotton a picker can carry without changing the volume. Modular units enable pickers to work with manageable quantities, which can be easily adopted into existing carry-and-store practices (i.e. saree, shoulder bag, basket) [6] or transported with nontraditional methods.

This strategy's feasibility depends on the force and energy needed to compress cotton to the desired level. Pressure vs size reduction was measured by creating a cotton-filled rigid box from foamboard. String attached the movable cover to a spring scale, which measured applied force. Pulling the spring scale applied the force on the cover, compressing the cotton below it. The height of the cotton gave an indication of the level of compression. The experiment results are shown in **Figure 4**, and indicate that the force to compress cotton increases exponentially. Beyond a 60% compression, cotton becomes exponentially difficult to compress manually.

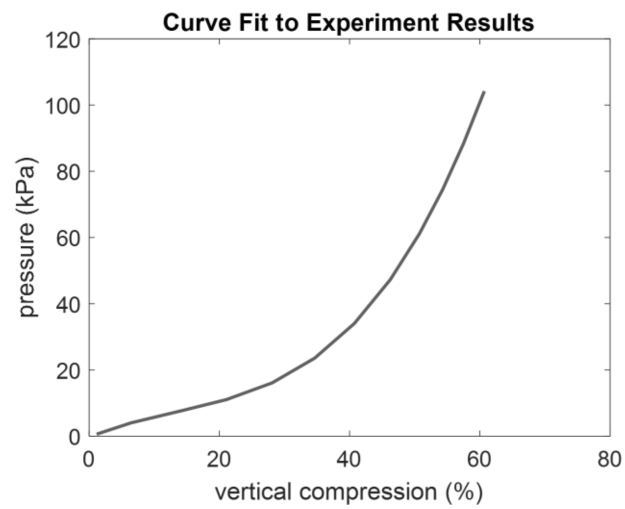

Figure 4: Pressure versus size reduction with experimental setup

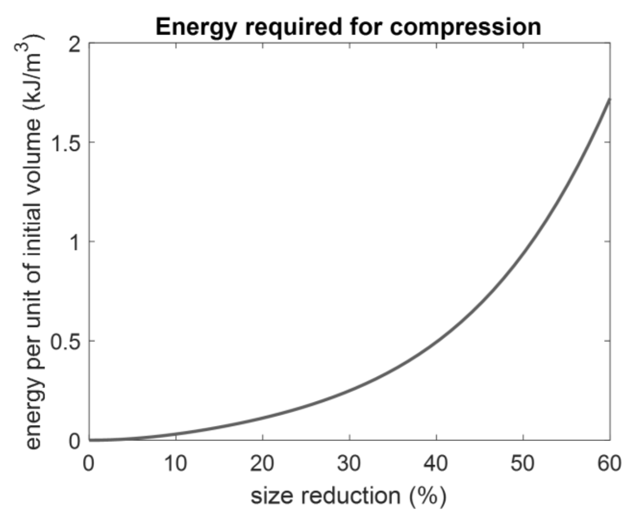

Figure 5: minimum energy required to compress. Actual energy spent by human may be more due to inefficiencies in energy delivery.

These results agree with published work stating Cotton is a natural plant fiber with a non-linear stress-strain behavior [13, 14]. A third order polynomial was fit to the experimental results of **Figure 4** and integrated to obtain **Figure 5.** From **Figure 5** one can calculate the power required to compress cotton. For example, the minimum average power required to compress 5L of cotton by 50% in 1 second is 4.75W. Actual applied power is expected to be higher. It was also found that long compressions (e.g. inside a tall cylinder) resulted in high frictional forces at container walls, which could affect these results. Short compressions (i.e. low height shapes if compressing vertically) are recommended.

The results demonstrate that high levels of compression (70% or higher) may not be a good return on human effort given the exponential growth of spent energy. The power required for compression is reasonable for humans using their hands and arms [16].

Interactions with cotton during experiments and prototyping also revealed that cotton rebounds significantly when released from compression. When compressed to 40% of its original volume, cotton springs back to 90% of its original volume. A method to maintain an even compressive force on cotton is necessary to fully utilize the benefits of a compression-based solution.

3. PROPOSED SOLUTION DESIGN

The proposed solution builds on the design of a roller-inspired cotton picker [10], and guides cotton from the picker into a bag, where it can be compressed through human power into a reduced-volume state that may be stored in a worker's saree, shoulder bag, or basket or on the to-be-introduced carrier. The design features of the picker-bag integration mechanism, bag, bag-carrier integration mechanism, and carrier are as follow.

3.1 Bag-picker Integration

The bag-picker attachment module was built assuming a cotton picker design similar to the roller-inspired cotton picker described by [10]. Field testing in a cotton farm near Raleigh, North Carolina demonstrated several features were necessary to improve the picker's utility for workers before a bag-picker attachment module could be designed. The features are:

1. Rollers with an exposed area of 8 cm X 5 cm positioned at the tip of the picker to allow access to cotton bolls without obstruction from surrounding plant parts
2. A roller to bag distance of 0.3 - 0.4 m to facilitate alignment of the rollers to cotton bolls without obstruction from the attached bag
3. Inclusion of an angled wall and funnel that directs cotton into the attached bag
4. A handle for the worker to hold that minimizes bending or arching to reach cotton bolls
5. Placement of the handle at the opposite end of the rollers, behind the bag funnel and angled wall, to avoid collision between bag and worker limbs
6. An on-off trigger mechanism (e.g. switch, button) to save battery power
7. A shoulder strap to allow the cotton picker to wear the device when not in use
8. An overall picker weight of less than 500 g
9. A battery capable of providing 1.5 V and 1.2-2.5 A of power

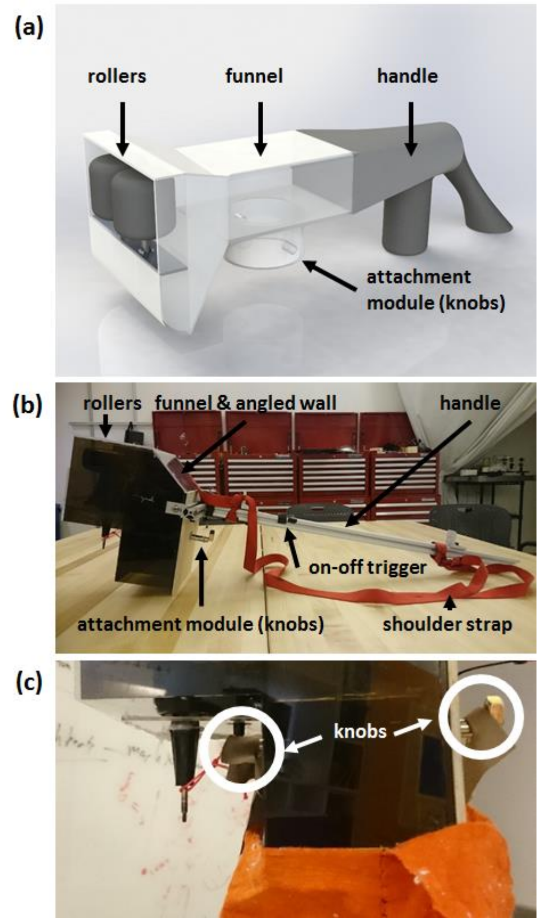

Figure 6: (a) CAD model and (b) prototype picker with (c) close-up of bag-picker attachment module

The CAD model and prototype picker in **Figure 6(a,b)** demonstrate some of these features. The proposed attachment module, shown in **Figure 6(c)**, consists of two knobs located at opposite ends of the bag funnel. Two tags at the bag opening are hooked onto these knobs to attach the bag to the picker. The module is sized to match the size of the bag opening, with a funnel exit smaller than the bag opening to ensure cotton cannot escape.

Attachment is a simple two-step process of looping each tag onto the corresponding knob (Figure 6(c)) The knobs feature a wider head than neck to prevent the bag from spontaneously detaching. Detachment is a similarly simple process of removing one tag, then the other. Both attaching and detaching can be done with one hand.

The knobs should be capable of supporting more than the weight of a full bag (approximately 600-700 g). Consequently, knobs must be stiff with adequate strength to prevent deflection and deformation from the bag weight, just long enough to allow the worker to easily loop bag onto picker, and light to minimize added weight to the picker. Knob area can be no larger than the bag tags' hole size.

3.2 Design of bag with cotton-compressing capability

The compression bag shown in **Figure 6** consists of a non-stretch fabric bag with two attached flat boards, two snap-fit buckle-and-pull-straps wrapped around the long edge of the bag, and an opening flap. Two tags at the opening allow the bag to be attached to the picker with ease, while a handle permits comfort during carrying and allows integration with the carrier.

Upon filling the bag, the worker detaches it, covers the opening with the flap, folds the bag, and buckles-and-pulls the two straps. Each strap is anchored to the bag near the opening, wraps completely around the bag, and has an extended section that the worker can hold and pull to tighten the strap. The tension in the straps applied by the worker transfers to the two boards attached to the bag in a 2:1 pulley system-like manner, compressing the cotton in between with a total force two times that applied by the worker, as shown in **Figure 7(d)**. To compress the bag shown in **Figure 7** by 60%, the tension applied on each strap through a pulling motion must be 60 N, which is within the capabilities of the average human [16]. The buckle-and-straps maintain the compressed state, continuously applying a force of 120 N each or 240 N total on the cotton. These calculations are shown below (reference **Figure 7**)

$$T = \frac{\sigma_{cotton} A_{board}}{4} \qquad \textbf{(2)}$$

$$T = \frac{(10kPa)(30cm\ x\ 8cm)}{4} \qquad \textbf{(3)}$$

$$T = 60N \qquad \textbf{(4)}$$

Where,

T = pulling force (tension) with each strap must be tightened

σ_{cotton} = Normal pressure applied by compressed cotton

A_{board} = Area of board pressing on cotton

The bag is sized to hold a mass of cotton equivalent to that stored in a saree, while maintaining dimensions appropriate for a human to carry. It has a width of 12 inches, a length of 18 inches, and a flap extending beyond the opening on one side by several centimeters. The flap covers the bag opening when it is not being filled, preventing cotton from falling out post-picking.

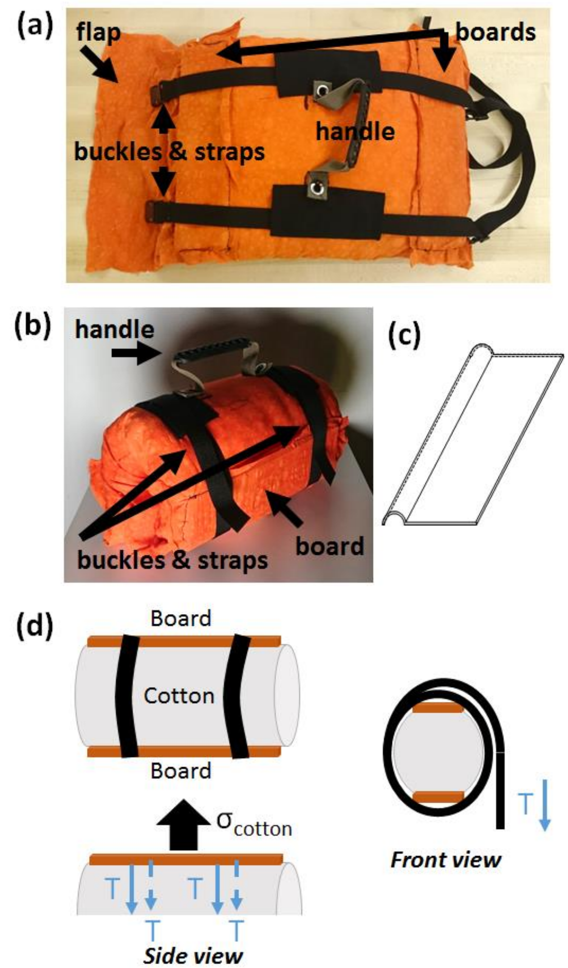

Figure 7: (a) Uncompressed bag and (b) compressed bag with (c) image of C-beam flat board and (d) strap tension calculation

Bags are made of non-stretch fabric to keep cotton compressed after tightening and reduce ballooning from the large springback effect. Suggested bag materials are cotton or nylon, though materials with similar characteristics can also be used--the bag material simply needs to be woven, non-stretch, and flexible, inexpensive, durable, easily cut and sewn, and lightweight. Cotton or nylon can also be printed on, producing aesthetic designs or personalization that may encourage product adoption.

Two rigid but light boards are sewn into the bag. These boards allow even compression along the width and some length of the bag, and withstand deflection from cotton springback. A large board area is desirable to maximize area of compression and minimize springback; however, board area is proportional to tension as shown in **Figure 7(d)**, which limits the maximum size the board can be. Additionally, board width must be several centimeters less than bag width to permit opening of the bag for filling due to the board's rigidity, and board length must be less than the diameter of the compressed bag to easily fold the bag. Rigidity in the board is provided by a C-beam that spans the board width, as shown in **Figure 7(c)**. The C-beam increases the board's moment of inertia and flexural strength. It is joined to a flat section that optimizes the compression area. The benefit of a C-beam over other beam structures is the absence of any sharp points on the outer side that can irritate workers. Polypropylene is the suggested C-beam material: the lightest commodity plastic, it is economical, chemically and heat resistant (compared to other plastics), tough, and resistant to fatigue.

Snap-fit buckle-and-straps provide the applied compressive force. A length of 1.5 times the bag length is recommended for each strap to provide the worker with a handle for pulling while minimizing excess strap. The buckle frame of each strap is anchored near the opening on the side with the flap (the outer side), while the buckle hook is loose. The loose strap is secured on the bag outer side to allow for motion along the bag length, but not the bag width.

3.3 Bag-carrier Integration

Once the bag has been compressed, it can be placed in the worker's traditional carry-on (e.g. saree). The worker may also use the carrier shown in **Figure 8** to increase the overall carrying capacity volume. The bag is transferred to the carrier through a guiding structure composed of a rigid rod joined to a flexible but stiff appendage. A handle located on the outer side of the bag allows the worker to loop the bag onto the appendage, which guides it to the rod that restrains it on the carrier.

The flexible appendage is kept to the left or right side of the worker's head, just out-of-view but within arms' reach. Its flexibility reduces the difficulty of orienting the bag in a specific position to guide it onto the rod. Little positioning is needed after releasing the bag onto the rod, as the bag will usually self-position into a compact stack, though the worker can quickly check by feel to ensure it has fallen long-side down.

3.4 Carrier

The carrier consists of a rigid and tough hiking backpack frame with padded shoulder straps and a padded waist buckle-and-strap. It is worn on the back. The rigid pole extends upwards from the base of the frame to the base of the neck, where it connects with the flexible appendage. In its current state, the carrier is manufactured from lightweight aluminum tubing, with the rigid pole made of PVC. The advantage of working with cotton storage is that, even in its maximally full state, the bag does not need to carry heavy loads. Thus, the materials out of which the bag is fabricated are not structurally significant so long as the rigid pole is supported. This delivers the ability to create an easily-manufacturable and low cost final carrier unit. The carrier is primarily designed to easily integrate with the bag system described above. As bags become full of cotton, the operator fixes the bag to the carrier, enabling an increased carrying capacity. As described in Section 3.3, the rigid rod and flexible connector allow for easy storage and stacking of the bags. As it stands with current testing, the carrier enables the operator to transport 6 - 8 bags of compressed cotton, which represents more than twice as much storage capacity than the saree method with compressed bags.

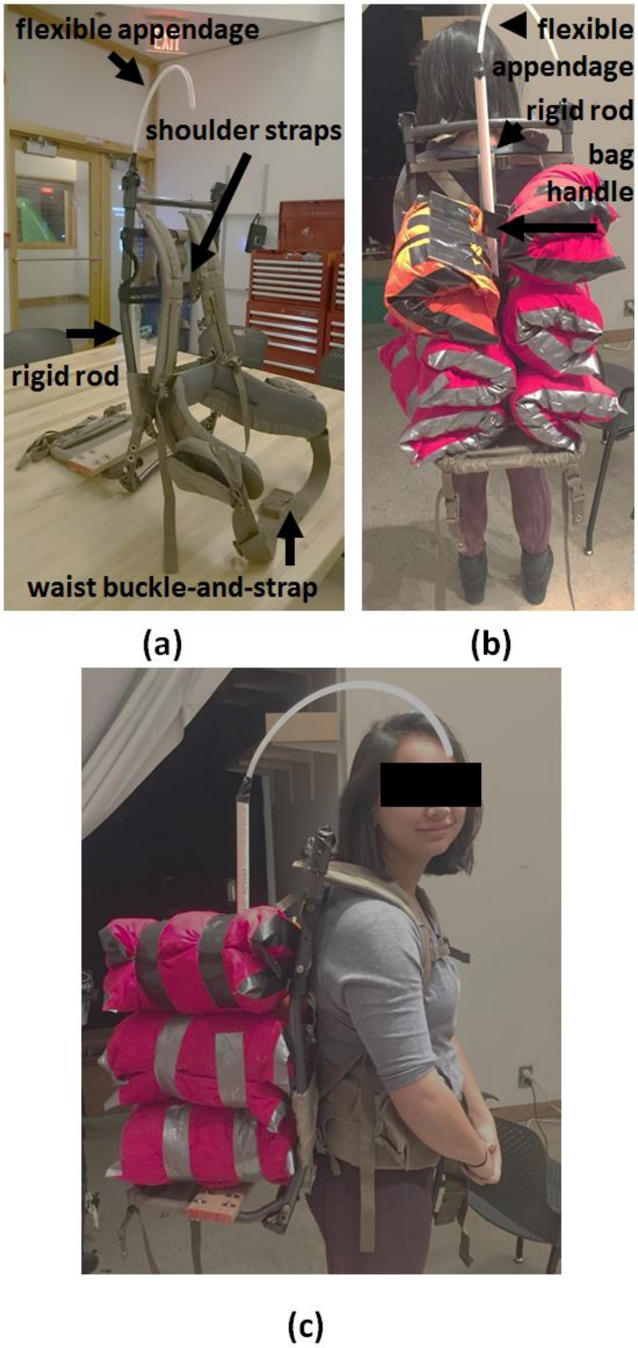

Figure 8: Carrier (a) front-side without bags, (b) back with bags, and (c) side with bags

The padded waist buckle-and-strap comfortably disperses the weight of the bag from the shoulders to the hips, as shown in **Figure 8(c)**. Without it, both the entire weight of the carrier and bags and the moment exerted on the worker by that weight would need to be balanced by the reaction forces and moment exerted by the workers' shoulders. The force diagram also implies that the smaller the distance between the carrier's moment of inertia and pivot point, the smaller the moment exerted on the worker and the more the weight is supported by the reaction force at the hips.

Carrier length is specified by row-to-row plant distance or human dimensions--whichever is smaller. The width of the carrier base matches the shoulder width of the average worker (~15 inches), while and the height matches the hip to head length of the average worker (~25 inches). In addition, the final design of the carrier will also be optimized to prevent the worker from overheating or experiencing an increased level of discomfort due to decreased ventilation as a result of wearing the carrier. This can primarily be achieved through the minimization of contact points between the carrier and the user's back, which will allow for the operator to wear the carrier without discomfort.

3.5 Testing

The effectiveness of the proposed solution was evaluated with user testing and modelling. Average and maximum bag volume and mass were measured to determine the compression achievable by human power and the approximate amount of cotton that can be packed in each bag. The authors wore first a saree and then the carrier to compare the total mass of cotton one can carry with and without the proposed solution, as well as ease of usage. The total time saved by enacting the proposed solution was evaluated using the simulation model described in section 5.

4. RESULTS

4.1 Cotton Compression

An experiment was designed to evaluate the actual compression achieved by the integrated picker-bag system. The bag prototype was attached to a shell of the previous roller prototype. Cotton was run through the rollers and into the bag until the bag was perceived to be full (e.g. when the cotton level began piling at the funnel exit). This mimics how workers will be relying on perception to determine if the bag is full and needs to be replaced. Once the bag was full, it was removed from the device and the cotton was compressed using the buckle-strap mechanism. The mass and final volume of the compressed bag were measured. An average of approximately 600 g of cotton was stored in each bag, equal to the amount of cotton stored in a saree. An average of 60% cotton volume reduction was achieved, which is the predicted maximum compression achievable through human power.

4.2 Carrying Capacity

Two methods of carrying cotton were tested to determine how much cotton could be carried in the compressed bags. The first method utilized the traditional saree. A maximum of three bags, two in front and one in the back, could be carried using this method. Beyond this point, the excess bag volume hindered worker mobility. Because the bags hold the same mass of uncompressed cotton as the original saree, using the traditional saree carrying method still resulted in a three times increase in carrying capacity.

The second method utilized the carrier in place of the saree. When the bags are aligned, as seen in **Figure 8(b)**, a maximum of eight bags can be carried using this method. Even when the bags are not aligned, causing each individual bag to effectively take up more space, a minimum of six bags can be carried. This resulted in a six to eight times increase in carrying capacity.

4.3 User Experience

The bags and carrier were designed for ease of use and ergonomics. The mass of the bag-picker system, with picker optimization by our agricultural industry partner, will be under the 500 g requirement. However, the pure mass of cotton that can be picked and stored in the bags is 600 g, exceeding the requirement. To accommodate this, the new picker prototype will be held with two hands and wielded like a shotgun. This provides greater support for the increasing mass of the system as cotton comes in. It also provides greater control and accuracy when aligning the picker with the cotton.

All steps in the process can be done with two hands. The bags can easily be put on and taken off of the picker by holding the picker with one hand and donning or doffing with the other hand. Because of cotton's frictional properties and the tangled condition of its fiber, the cotton stays inside the bag while the bag is taken off of the picker, preventing any loss of cotton if the bag is tipped on its side.

Compression of the bags can also be achieved using two hands. The picker will have a shoulder strap that allows it to hang freely from the worker without falling to the ground. The bag can be folded in half, the straps closed, and compressed using one hand for support and the other for operation. Approximately 60 N of force on the straps was required to compress each bag by 60%, which was the expected amount. Unloading of the bags simply requires unbuckling the straps and shaking the cotton out of the bag.

Transfer of the compressed bags to the carrier can be done using one or two hands, depending on skill level. User skill is also required to drop the bags into the carrier in a way such that they align to create the most efficient use of space, increasing the capacity of the bag. However, even if the bags are dropped in an unorganized way, the increase in carrying capacity is still significant, as explained in section 4.1. To accommodate the increased carrying capacity and therefore the increased mass on the worker, the carrier uses hip straps that distribute the weight along the user's hips instead of their shoulders, as mentioned in section 3.4 and seen in **Figure 8(c)**. This is a much more efficient use of the human body's larger muscle groups, especially for the mostly women workers.

An additional finding that the team was able to uncover through field testing of the previous team's design was the need to constrain the size of the rollers. From a user experience standpoint, large rollers will often get "caught" on other parts of the cotton plant and prohibit the operator from capturing only specific pieces of cotton. Thus, our final design included rollers that were approximately 2" (~2 cm) tall to allow the operator to easily align them with individual cotton bolls and successfully pull in only cotton while minimizing the inclusion of debris.

4.4 Cotton Protection

The presence of trash (dirt, leaves, other debris) in the cotton decreases its value. Therefore, it is important to the farmer to maintain the purity of the cotton. With the cotton contained in the compressible bags, it is protected while in transport until it is unloaded in the central location. This prevents excess trash from getting into the cotton after it has been collected through the rollers.

Due to its modularity and low density, free cotton is prone to being dropped or blown from the worker's hand or saree. In the compressed bag, however, the cotton is packed to a point that is too heavy to be blown away. Additionally, even if the bag is dropped, the bag will prevent cotton from being lost.

4.5 Cost

The overall device, including the picker, bags, and carrier, must be under 7000 INR (~$100). The cost of the previous picker prototype has not yet been determined as our agricultural industry partner is in the process of optimizing it. However, competitor pickers currently on the market sell for an average of 4500 INR (~$67). This can be used as an upper-bound estimate for the cost of the picker. The costs of bags and carriers have been estimated from the price of similar products manufactured and sold in India. Each bag could cost approximately 45 INR (~$0.65). If the worker is using a saree, they can carry up to three bags, totaling 135 INR (~$2). If the worker is using the carrier, they can carry up to eight bags, totaling 360 INR (~$5.30). The carrier itself costs approximately 365 INR (~$5.40). In total, the overall system costs 5225 INR (~$77). Due to its modularity, the parts can be purchased and used separately. Therefore, the price of the product ranges from 135 INR using only three bags, to 5225 INR using the whole system. The price of the bags and carriers are estimates, if it is assumed that those prices were actually double of the number predicted here the costs to purchase would then be 270 INR for only three bags or 5930INR for the whole system.

5. PROCESS ANALYSIS

5.1 Cotton Picking Model

To verify our assertions regarding carrying capacity, we developed a simulation in MATLAB that could calculate the amount of time it would take to pick cotton from an arbitrarily-sized field. The MATLAB code can be found in the Appendix. Various inputs can be adjusted, such as the amount of cotton plants per square meter, the size and shape of the field, the amount of time spent walking from plant to plant, the carrying capacity, and other important metrics.

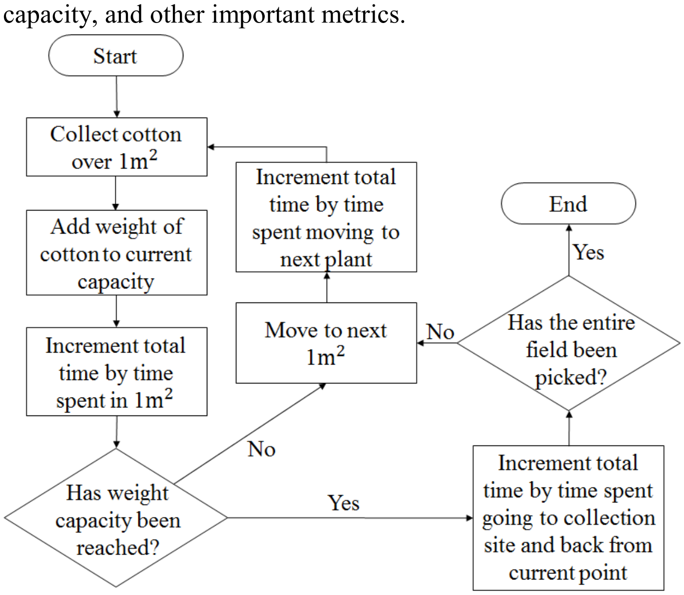

Figure 9: Flowchart of cotton picking model

A flowchart of the model is shown in **Figure 9**. The simulation draws out a rectangular field of a specified aspect ratio and populates the field with cotton plants. A worker with a stated carrying capacity navigates the field, picking cotton row-by-row. As the worker picks cotton, the cotton's weight is added to the saved current load (a measure of how much cotton the worker is currently carrying). As each worker action is done, the preset time that it takes to complete each action is added to the total time spent picking cotton. The saved current load measure is compared to the carrying capacity after a cotton flower is picked. When the saved current load just exceeds the carrying capacity, the simulation adds double the amount of time it takes to walk from that particular cotton plant to the set collection site since this is a round trip. This process continues until the entire field is picked, after which the time it takes to traverse from the last cotton plant to the collection site is added to the total time. Once the total time is calculated, the total time can be divided by the number of workers to obtain an average metric for the amount of time each worker would spend picking on the cotton field.

5.2 Process Improvements

In our simulation, we tested various inputs to examine their effect on the time saved. To test our hypothesis that increasing carrying capacity would decrease total time spent in the field, we adjusted these parameters in our model. Using various sizes of fields from 2 to 5 acres as well as doubling the carrying capacity from 1.5 kg to 3 kg, we found that the improvement in time ranged from 16 - 20%. This result increases as the field size or the elongation of the field (how far it differs from being square-shaped) increases. As carrying capacity is increased, its effect on the minimization of total time becomes less and less pronounced. The total time approaches an asymptote at the amount of time required to just pick the cotton from the field (without bringing the cotton to any collection site).

We used the model to gain insight and verify our assertions explained earlier. For example, the model predicted that given a 4 acre field, 85% of the total working time is spent moving from plant to plant as well as back and forth to and from the collection site. Only 15% of the total time on the field is spent actually picking the cotton. Thus, the greatest opportunity for reduction can be found in reducing the time spent walking. As a side note, we see that this value differs slightly from the experimentally found 75%-25% split in moving and picking. Our model can be made more accurate in the future by going out into the field and measuring all of our input parameters with greater precision.

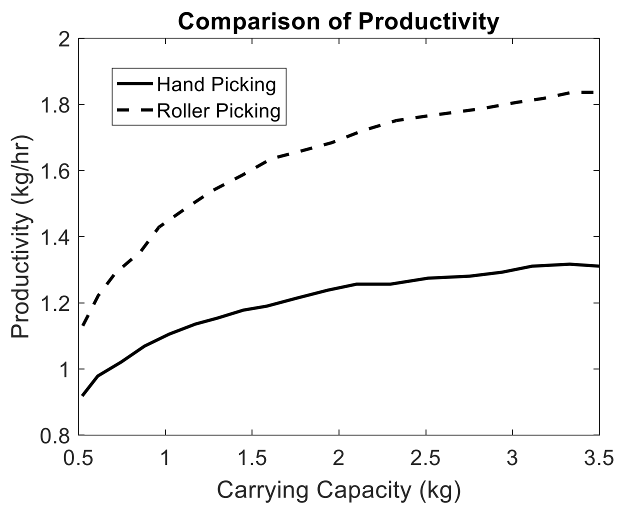

Figure 10: Plot of worker productivity versus carrying capacity with roller and hand picking

We were also able to see the amount of time saving that resulted from using the roller system, the bag compression system, or a combination of the two (**Figure 10**). The solid curve represents using the traditional method of picking cotton to determine productivity rate as a function of carrying capacity. The dotted curve represents the same function, but using the roller system. From the graph, we can see the improvement in the productivity that results from using these systems.

The current model-predicted productivity rate is 0.92 kg/hr at carrying capacity of 500 g. By using the roller system, we can increase the productivity rate to 1.14 kg/hr (illustrated by moving from the left end of the solid curve to the left end of the dotted curve). By using the compression bags explained earlier, we can move along each of the curves, further increasing productivity. Using the compression bags with the current saree-based carrying system, we see an improvement to 1.6 kg. By using our backpack system to increase carrying capacity even more, we can increase the productivity rate to 1.79 kg, which is a 95% increase from the traditional method of picking and carrying cotton. Thus, we can achieve nearly 2X improvement using the roller system, the compression bags, and the backpack.

From this graph, we can also see that the compression bags compound the advantages of faster picking. Essentially, the picker shifts the bottleneck from picking to carrying capacity, while the compression bags reduce the effect of that shifted bottleneck. This is why the curve increases more sharply for the roller-picker method than the hand-picking method.

We were also able to disprove certain methods using the model. For example, one of our initial process improvement ideas was to have the workers drop the bags on the field instead of carrying them back to the collection site. However, the model predicted that this workflow would require over 1300 bags to implement, which is surely outside of the economic constraints of the farmers.

These data allowed us to decide on adequate design parameters for our apparatus that would allow more cotton to be carried at one time. Given that we ran simulations with a collection site quite near to the field, the effect of increased carrying capacity is much more pronounced as the collection site is moved further from the field. We would have to verify this with actual cotton field dimensions and data.

5.3 Financial Performance

A critical goal for this project was not only to reduce farmer dependence on scarce manual labor, but to create an affordable solution that would improve farmer livelihoods by reducing labor costs. In order to accomplish that, the team aimed to use abundant, cheap materials that could be easily manufactured in India, such as plastic, cotton, and aluminum. The breakdown of the anticipated cost structure was covered in section 4.5. The next step was to assess the savings achieved by the 2X productivity improvement in order to determine the expected payback period for the system.

Current wages for agricultural labor in India, as mentioned in Section 1.2, are set by the MGNREGA law. The team used a conservative estimate for wages, 240 INR per worker per day, which represents a 20% premium on top of the high-end of the permitted range for minimum wages (200 INR). Using the data that our agricultural industry partner shared claiming that it takes 30 man-days of labor to harvest the cotton from a single acre, an estimate was established for the labor costs of a single harvest on a 4 acre farm: 28,800 INR. This calculation represents the wage (240 INR) multiplied by the labor required (30 man-days per acre) and the number of acres (4).

With the current labor costs established, the team was able to forecast labor costs with a 2X improvement in productivity: 14,400 INR. The team expects the system to reduce the labor required for a single harvest from 30 man-days per acre to 15. Using these data, it was determined that the savings would also be 14,400 INR. However, because there are 5 harvests through the cotton season in India, total savings in one year from the implementation of the system would be closer to 72,000 INR.

Using the cost estimates from section 4.5, it can be assumed that the cost of a complete system, consisting of a picking device, a carrier, and eight compression bags, will be roughly 5,225 INR in the beginning of 2017. Including a 40% markup, the total cost would be roughly 7,315 INR. Determining the payback period for the farmer's investment in the system then depends on the number of complete systems he decides to purchase. If, for example, the farmer decided to purchase 5 complete systems, at a total of 36,575 INR, the payback period would be 0.51 seasons. If he wanted to purchase 10 complete systems, at a total cost of 73,150 INR, the payback period would be 1.02 seasons.

6. CONCLUSIONS

6.1 Summary of Results

This project aimed to expand on the previous work described in [10, 11] to achieve a 3X productivity improvement in the picking of cotton on farms in India. Due to the unique characteristics of the Indian market, such as the small and irregular size of Indian cotton farms, capital constraints, etc., previously developed mechanical harvesting solutions could not be applied in this context. This provided the impetus for the work conducted by [10][11] and the present team.

After the initial research phase, the team recognized the necessity of approaching the problem posed by our agricultural industry partner as one needing both systems and mechanical engineering. By using this lens to look at the problem, combined with the analysis of the MATLAB situation, the team was able to determine at the start that a compression-based solution would be required to make meaningful progress towards the requested 3X productivity improvement. Rather than viewing the variability of farm size, layout, and processes as a set of constraints, the team recognized that there could instead be "design freedoms" that enabled the creation of a modular solution that would work in many scenarios found in the cotton fields of India.

The team conducted thorough research on the characteristics of cotton compression, determining that compression beyond 60% requires more power than the workers themselves could produce or reliably access on the fields. These set parameters for the development of the compression bag. The team decided to leverage human mechanical advantage, stabilized cotton bags, and snap-fit buckle-and-straps in order to achieve the goal of 60% compression of the bag.

Once the team developed the compression-based bag design, attention turned to creating a carrier that would enable the worker to carry more cotton at one time. The team focused on this approach in order to reduce the number of times a worker would need to walk to intermediate and central storage points throughout the work day. The carrier was designed to use the worker's hips as a platform for supporting the weight of the carrier itself and the bags it was designed to hold. The bag-carrier integration was designed to maximize the number of compression bags that could be carried, while making it easy for the worker to add the bag to the carrier and shift it once it had fallen to the bottom of the pole.

After re-evaluating the harvesting process at the farm level using the new system, the team anticipates that the farmers will witness a 2X improvement in the productivity of their workers.

6.2 Ramifications

The anticipated 2X improvement in productivity of cotton harvesting will have major ramifications for the Indian cotton market. As outlined in Section 1.3, the harvesting process in India is entirely manual, and reliance on a declining rural labor force is creating a formidable challenge for cotton farmers. By dramatically increasing the productivity of the workers that remain with a low-cost device, farmers stand to not only fully capitalize on the crops they are able to grow but to improve their margins and create more income for their families. The team was initially wary of the impact that the system would have on the workers in rural areas in India, but it became clear through more research that this approach would not reduce the wellbeing of the workers and would instead create the potential for farmers to increase their standard of living.

The project also had ramifications for the team's own learning. While the team was initially planning to approach the problem from an entirely mechanical point of view, it became clear very quickly that the problem the farmers were experiencing was rooted as much in larger social systems and on-farm processes as it was in a lack of a technological solution. By understanding this reality and working to identify the constraints and opportunities that it presented, the team was able to identify the "design freedoms" mentioned in Section 6.1 that made the modular approach to the system design valuable. The team was also able to determine, using the MATLAB simulation, that our agricultural industry partner's goal of achieving a 3X improvement in picking productivity is not feasible from a purely technological perspective, and it would instead be needed to find a way to change farmer and worker behaviors and practices to order to accomplish it.

6.3 Future Work

Refining the design of the system is the main priority for future work on this project. While the team created a functioning prototype of each part of the system (bag, carrier, bag-carrier integration) that would effectively demonstrate the concept to the client, there is still work to be done on the overall design of the device. For example, field testing showed that the size of the device needs to be optimized to fit between the branches of the cotton plants. This will likely require refinement of the roller module created by [10, 11] with respect to size, speed, and power. Field testing showed that substantial work remains to determine the optimal size of the rollers, the speed at which they spin, and the power required to keep the device running throughout the entire 8-hour day in the field.

Once the roller module has been refined, it will serve as the starting point for the optimization of the design of the rest of the system, with the ultimate goal of achieving a manufacturable design that is both comfortable and accepted by workers. This will require human factors testing to find the most desirable length of the device and the size and shape of the carrier. Additional testing and iteration are required to determine the optimal size and design of the bag, as well as the integration points for the bag and device and bag and carrier.

ACKNOWLEDGMENTS

The team thanks our partner, Mahindra, for the continuous discussion and feedback, as well as Michael Buchman for his valuable guidance and feedback.

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ANNEX A

MATLAB SIMULATION CODE

```
%% INFORMATION

        time_Enter = 41;      % [s]      Entering and exiting the field
        time_Sack = 41;       % [s]      Placing collection sack

        time_Reaching = 1;               % [s]      Reaching flower
        time_Holding = 1;     % [s]      Holding flower
        time_Plucking = 1;    % [s]      Plucking cotton flower from plant
        time_Putting = 1;     % [s]      Putting cotton in  cloth pocket (saree)

        time_Bag = 15;        % [s]      Emptying and reloading a bag to the picker

        time_Moving = 5;      % [s]      Moving from one plant to another
        time_Transfer = 89; % [s]        Transferring cotton to collection sack
        time_Compacting = 14;   % [s]            Compacting
        time_Packing = 8;     % [s]      Packing the sack
        time_Trolley = 8;     % [s]      Movement of trolley

        field_Acre = 4;       % [acre]   Size of the field in acres
        field_AspectRatio = 1;  % []     Ratio of width to length (1 is a square)
        plants_SqMeter = 4;              % [num]   Cotton plants per square meter
        kg_Plant = 0.010;     % [kg]     Kilograms of cotton per plant
        flowers_Plant = 5;    % [flowers] Flowers per plant

        kg_Capacity_Const = 1;           % [kg]    Kilograms of cotton that a single person can hold
        bag_Individual_Capacity = 0.5 % [kg]     How many kg of cotton an individual bag can hold
        bag_Capacity = 6;   % [bags]  How many bags used per trip
        num_Workers = 1;                 % [num]   Number of workers in the field
        walking_Speed = 0.5;             % [m/s]   Walking speed in meters per second

%% SIMULATION

% Generates a cotton field

        kg_SqMeter = kg_Plant*plants_SqMeter;
        field_SqMeter = field_Acre*4047;
        perimeterMultiplier = sqrt(field_SqMeter/field_AspectRatio);
        field_Width = round(field_AspectRatio*perimeterMultiplier)
        field_Length = round(perimeterMultiplier)
        total_kg = kg_SqMeter*field_SqMeter;

% Walk through cotton field

        arrayTimes = zeros(1,10);
        arrayCapacity = zeros(1,10);

for i=1:1:100
        fieldComplete = 0;
        time_Total = 0;
        time_PickPick = 0;
```

```
            time_MoveMove = 0;
            currentX = 1;
            currentY = 1;
            collectionPointX = -100;
            collectionPointY = -10;
            sack_CurrentCapacity = 0;

            time_PerPlant = flowers_Plant*(time_Reaching+time_Holding+time_Plucking+time_Putting);
 %   time_PerPlant = (100-i)/100*time_PerPlant
            time_PickPick = flowers_Plant*(time_Reaching+time_Holding+time_Plucking+time_Putting);

            kg_Capacity = i/20*kg_Capacity_Const;
 %   kg_Capacity = 2.5;
            bag_Capacity = round(kg_Capacity/bag_Individual_Capacity);
            bags_used = bag_Capacity;



            while(fieldComplete == 0)
            sack_CurrentCapacity = kg_SqMeter + sack_CurrentCapacity;
            time_Total = (time_PerPlant+time_Moving)*plants_SqMeter + time_Total;
            time_PickPick = flowers_Plant*(time_Reaching+time_Holding+time_Plucking+time_Putting) + time_PickPick;

            if(sack_CurrentCapacity > kg_Capacity)
            time_Total = 2*sqrt((currentX-collectionPointX)^2+(currentY-collectionPointY)^2)/walking_Speed + time_Bag*bag_Capacity + time_Total;
            time_MoveMove = 2*sqrt((currentX-collectionPointX)^2+(currentY-collectionPointY)^2)/walking_Speed + time_Bag*bag_Capacity +
time_Total;
            sack_CurrentCapacity = 0;
            bags_used = bags_used + bag_Capacity;
            end

            if((currentX+1)>field_Width)
            if((currentY+1)>field_Length)
            time_Total = sqrt((field_Width-collectionPointX)^2+(field_Length-collectionPointY)^2)/walking_Speed + time_Bag*bag_Capacity + time_Total;
% The final walk back to the collection site
            time_MoveMove = sqrt((field_Width-collectionPointX)^2+(field_Length-collectionPointY)^2)/walking_Speed + time_Bag*bag_Capacity +
time_Total;
            fieldComplete = 1;  % The field is completely finished
            else
            currentY = currentY+1; % Walk row by row
            currentX = 1;
            end
            else
            currentX = currentX+1; % Move left to right
            end
            end

            arrayCapacity(i) = kg_Capacity;
            arrayTimes(i) = (total_kg)/(time_Total/3600/num_Workers);

            time_PickPick/(time_PickPick+time_MoveMove)
            time_MoveMove/(time_PickPick+time_MoveMove)
end

            plot(arrayCapacity,arrayTimes)
            time_Total/3600
            bags_used/num_Workers
```