Exploring a novel cable based architecture for an agricultural robotics platform

by

Jayanth Mohan Kumar

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Author . . . .
System Design and Management Program
23rd May, 2022

Certified by . . . .
Dr. Bryan R Moser
Academic Director, System Design and Management Program
Thesis Supervisor

Accepted by . . . .
Joan S Rubin
Executive director, System Design and Management Program

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Abstract

This thesis examines a potential new architecture for Agri-robotics. A series of architectural decisions are examined and evaluated against a pre-populated problem space foccusing on labour intensive low land use crops. The evaluation also consists of performance metrics at an L1 level and evaluation of the solution space using methods from MDO. The architecture is then compared to existing and near future alternatives and future work is suggested.

Thesis Supervisor: Dr. Bryan R Moser
Title: Academic Director, System Design and Management Program

Contents

List of Figures

Chapter 1

Introduction

Agricultural robotics are the next frontier for improving productivity and lowering food cost for a world with a growing population that is expected to only stabilise by 2100.

Most work in the literature currently focuses on the end-effector and control algorithm design to enable specific high human involvement operations like selective spraying, pruning, harvesting and weeding and the detailed design for these operations.

A fundamental problem that has not been explored in detail is the platform on which these robotic systems are going to use to move around the field. The dominant platform architecture for the approximately the last 130 years has been the tractor. This has led to the industrialisation of agriculture and the development of an extensive range of attachments and tools designed to work with the tractor. With such a dominant position even the process and methodologies of growing crops has evolved around it.

This effect has primarily been felt in crops where automation does not require fine control and could be done with mostly mechanical means for all operations required to grow the crop. The reduction in prices of starchy crops and the increase in farm size growing these crops has been the biggest change as a result.

The evolution of agricultural mechanisation has been one where cheap energy from fossil fuels has driven a large increase in productivity by doing bulk operations across the large tracts of land. To meet climate change goals a decrease in land area used by increasing productivity and a change in the source of energy for agriculture will be essential. Food prices and oil prices are directly linked **(quote the inflation study)**.

This trend of resource utilization efficiency has been driven by either resource constraints or cost. With climate change goals in mind this trend will accelerate with the added constraint of reducing green house gas emissions and other negative impacts on the environment.

Whenever resource efficiency is required in agriculture the obvious solution has been to look at how to optimise the inputs given for the yield obtained. These metrics vary based on whether the cost functions are based in economic output or just technical efficiency of the yield of crop per unit area farmed.

This has led to a trend of looking at smaller sections of the farm to infer the amount of inputs as well as the timing of these inputs required all the way to precision agriculture where the end goal is to look at each individual plant on the field to provide the optimal conditions for growth and yield.

When looking at the land area under cultivation and the revenue per acre as collected by the USDA one sees this vast gap between crops that are grown with high levels of automation and ones that still require a significant amount of human involvement. We see 3% of the land area accounts for 35% of the revenue in the US. [MacDonald et al., 2013] This is mainly due to the amount of human effort required to grow these high value crops. Given the work that is being pursued to automate these operations the time is right to examine the platforms that are used and compare it to the one proposed.

The thesis introduces and evaluates a new platform architecture that targets these crops that still require high levels of human involvement to produce.

1.1 Ideal requirements to enable the new class of tools

Robotics that can perform complex operations that are being currently developed that could replace human only tasks have very different requirements to those that have been designed with the tractor in mind. The choice is between replacing it with a new architecture or by adapting the robotic systems to function optimally with a tractor like mode of operation.

One of the major limitations of these robotic end effectors is that they are extremely slow, typically 50% or lower than an equivalent human performing the same task that would require gripping or other physical manipulation. The amount of time that it takes for these systems to perform the operation is significantly longer as they need to perceive, infer, plan, then act. This calls for a platform that has low cost per hour of presence on the field.

Tractors optimally operate between 5-15 kmph and most of them require a human to be present to operate. Lowering the speed operation of a tractor is extremely expensive and wasteful in terms of energy and capital. The solution to this has been to increase the parallelism of the robotic tools while adapting them to use on a tractor as in the case of the blue river weed spraying technology where the number of sprayers was increased.

The typical mode of power transfer between the platform in a tractor is a power take off shaft that provides torque, but most robotic end effectors require only electricity and limited reaction torque. The conversion efficiency from diesel (most commonly used fuel source) to electrical power in such an application is extremely low. The power requirements are significantly lower as well as instead of performing bulk operations these systems perform smaller operations with more precision.

For information gathering operations endurance is key. What was exclusively a human domain with "farm walks" has now been augmented by either drones, satellite data or the tractor with sensors as an information gathering platform when it is operating on the field. The level of detail and the types of data that can be gathered are vastly different between these systems, however tools are being developed where the detail and types of data that can be gathered is increasing exponentially.

The ideal requirements of such a platform would be:

- No human operator requirement
- High flexibility to support a wide range of tools and operations
- High endurance and low cost per hour
- Large amounts of energy transfer
- Large amounts of mass transfer
- Low power
- Capital efficient

1.2 The proposed architecture

Cable based machines have been in use since the pulley was invented. They are now highly evolved machines that are used to lift loads, move people over long distances, etc. However fully cable based robots are relatively new with cranes and derricks being the most common partially cable based versions.

The proposed architecture is a 4 or more column frame at the edges of the area to be farmed with individual servo motors and brakes on each column that are then linked to a single platform that can move with 3 Degrees Of Freedom of translation. It will use the tension of the cables and gravity to prevent rotation in 3 directions to provide a stable platform for the end effectors and other tools to operate on the crop.

The proposed system will also have a mechanism to change tools either automatically or manually as well as the ability to send power and mass along the cables, this allows the platform to be grid connected for both water and power.

The dynamics of these machines are quite complex as all the cables need to be in tension at all positions in the work volume and the lack of rigidity requires adaptive control for positioning and stability, this however is a solved problem.

insert figure of concept sketch

Chapter 2

Literature Survey

Evaluating a new system architecture requires a broad set of areas that would adequately capture the system in its entirety as well as capture reasonable estimates of the interactions at the boundary. As a consequence of that the review has been divided into a set of sections that examine these areas required for the analysis.

2.1 Food and Nutrition

Most estimates of world population growth tend towards a value of 9.5 Billion by 2050 and food requirements that are proportional to that population. What is different however is that as wealth in developing nations increases the proportion of food that comes from low value high starch products drops. [1]A. Regmi and M. Gehlhar, "New Directions in Global Food Markets," p. 14. The paper predicts a shift towards higher quality sources of nutrition that would come from what are traditionally considered high value crops and protein sources that move towards meat and dairy. Sustaining this consumption trend would require significant increase in agriculture productivity.

A key factor even in developed markets is the ability to afford higher quality nutrition to improve health outcomes. Looking at factors affecting pricing of food, Lambert and Miljkovic analysed data from 1970-2009 looking at both endogenous and exogenous factors and came to the conclusion that wages for labor account for about 38% of overall cost. [Lambert and Miljkovic, 2010] [1]D. K. Lambert and D.

Miljkovic, “The sources of variability in U.S. food prices,” Journal of Policy Modeling, vol. 32, no. 2, pp. 210–222, Mar. 2010, doi: 10.1016/j.jpolmod.2010.01.001.

There are further studies by other authors that show the same non linear linkage between food prices and oil. Oil prices tend to only affect crops that could be used for biofuel production such as corn and soybean.[Reboredo, 2012][1]J. C. Reboredo, “Do food and oil prices co-move?,” Energy Policy, vol. 49, pp. 456–467, Oct. 2012, doi: 10.1016/j.enpol.2012.06.035. These crops are however not a focus of this thesis as the production cost of these crops are already highly optimised for production at scale with tractors.

The primary source of nutrient recommendations for Americans is the dietary guidelines book released by the departments of Health and Human Services as well as the department of Agriculture.

Looking through their recommendations for the ideal diet and the changes that they recommend to the diets of most Americans currently one sees that Americans in general consume foods that are energy dense but nutritionally sparse.

Over 80% of the population do not meet their recommended dietary intakes of vegetables and over 60% for fruit.

However for grains, over 50% of the population consumes at or above the limit.

The dietary trends of the developing world will follow similar trends and this is proven out in the increase in animal product consumption and increase in obesity as incomes rise.

Given the trend to limit energy content in food consumed and the increased focus on nutritional quality an index called the Nutrient Rich Foods index was created. **Adam Drewnoski** in his paper looks at the combination of NRF index as well as USDA nutrition composition and food price data sets to see if a dollar optimized diet that can maximize nutrients and minimize the 3 nutrient groups of sodium sugar and Saturated fat. However this work takes into account only the 9 major nutrient groups to maximise and does not capture the full set.

In the analysis which looks at a variety of food groups, vegetables, fruits and nuts provided some of the highest nutritional value but at high dollar cost per calorie.

When reexamining the USDA reports on trends of revenue and costs of production of these nutrient dense foods we see that reducing human labor cost is the only way forward to provide lower cost high nutrition value food for the expected population size.

2.2 System level analysis of automation in agriculture

Examining the system level impacts of robotics on agriculture has been relatively recent. While extensive studies have been performed on productivity of tractors and other semi autonomous machines that perform standard operations, the study of fully autonomous robotic machines that can adapt to non standardised tasks and operate in unstructured environments is relatively recent.

A first approach for the comparison between conventional and autonomous systems, in terms of their economic feasibility and potential for labour substitution, was presented by Sørensen et al. (2005). They surmised that the near and long term future of the amount of automation will primarily depend on compute cost and the potential for full automation. With the order of task replacement in the field being routine tasks first and then to non routine that are harder to perform. Where the Pareto optimal point varies with the "routineness" of the task vs the cost of developing systems to perform the non routine and high skill tasks.

A level of labour substitution will be reached for a particular technology level and labor cost, they however do not come to a conclusion on what the appropriate level will be, stating that there are a lot of systemic effects that are not captured. They also claim, that introduction of these systems where the entire system is designed to take advantage of the advantages offered will be a possibility for countries where adoption of routine automation is low.

A second work on the system analysis and feasibility assessment of robotic systems in agriculture was presented by Pedersen et al. (2006).

In their work, an evaluation of the impact of the implementation of innovative technologies (robotic weeding, crop scouting and grass cutting).

In their work, three applications of robotics implementation in agricultural operations executed conventionally by human-labor were examined, namely: field scouting (cereals), weeding (sugar beet), and grass cutting (golf courses).

With field scouting they note the possible measurements of different values and the sensor types required to measure those metrics on the field. One of the fundamental problems to solve is the detection of weeds. This is the detailed use case studied and they found that the costs are lower by about 20% if the resulting information is used for patch spraying of inputs instead of bulk. They similarly examined the use case of robotic weeding and found that the savings were not as high and would require much higher capacity platform for it to be viable with a base case interest rate of 5

The most recent system level economic analysis was by [Lampridi et al., 2019]. They propose a methodology that takes into account more systemic effects than the previous work. Including soil fertility, increased precision, added value of optimization of individual operations, etc.

They use a metric called field efficiency that is the agronomic time available to perform a task in the field. It includes a workability coefficient to account for task complexity for the equipment being evaluated. They also have details about idle time due to battery recharging, implement change, transport between fields etc. The cost model is split into ownership and operating costs with repair and maintenance being estimated from a paper by Bubeck et al.

They examine this system with two case studies, the small scale farm with a 10 ha and a large scale farm with 100 ha farm size. They also used a sizing estimate based on the workability and the power of the tractors or number of robots were selected for the analysis.

The conclude with a set of cost comparisons for the cases analyzed with cost ratios that range from 1.36 to 1.9 times the cost of a conventional system. They qualify their findings however because of the assumptions made about the performance of the robotic systems parameters and values such as reliability and salvage value that will affect the cost comparison.

With any new technology adoption is an important part of the system level analysis. A study in Germany by [Michels et al., 2021] shows that NPV alone is not enough to drive adoption. It is primarily driven by the perceived ease of use and hence the perception of whether the value of the system will be realised and not an idealised case of the value generated.

Most robotic systems economic analysis has been based on estimating effectiveness of various automation technologies. The analysis has typically been formulated as a linear optimisation problem with cost functions related to labour rates and machine per hour costs with large assumptions about technical performance of the fully autonomous system but good estimates of the standard processes.

2.2.1 Metrics for measuring the impact of a robotic system on field productivity

Given the types of analysis done previously to measure the impact of fully autonomous systems on the basis of cost, one aspect missing has been the ability to account for the improvement in productivity based on the ability to make decisions and provide inputs at the sub-field level, possibly even the plant level.

To measure cost per acre for a robotic platform one needs to keep the biological and other input quality identical as well as the Agro-climatic potential.

The Food and Agriculture Organisation report on Farm productivity and efficiency measurement (2017) goes into a comparison of the various measures proposed and used both by the USDA and across the world. For our needs an input quality independent metric would be most appropriate.

They define Technical efficiency as the maximum theoretical potential for a given process, set of inputs and crop in a particular Agro-climatic condition, there exists a maximum potential yield of crop per unit area of land. The efficiency measured is how close the best possible yield is to the potential yield possible.

While evaluating an new architecture, dollar costs are not a reliable estimate for our analysis as they are measured by cost accounting for labour pricing and other input pricing in a variety of markets. There is also a significant amount of influence by improvement in process or plant breed which does not impact a platform architectural comparison. However the data to examine potential yield improvements from the adoption of precision agriculture is unavailable but detailed cost estimates are available for some markets for standard processes. Comparing a real world workload against these estimates would provide a reasonable metric to analyse.

2.3 Advantages of subfield level optimisation

Highly autonomous robots enable subfield level manipulation and decision making. Presented here are some of the key operations and the potential optimisation possible with such platforms. The key advantages with such platforms lies in their ability to take decisions at the subfield possibly even the plant level and also take the required action to correct or enable the individual plant to do its best.

2.3.1 Automated weeding

Weed removal is a key operation that impacts the yield and the profitability of the farm. Many studies have been performed to examine this effect.

A study by Hodgson showed a reduction of 50% in California lettuce fields. Monaco et al found upto a 71% reduction of yield in direct seeded tomatoes when competing multiple weeds at low density of 11 weeds / m2.

Weed management has been solved by many techniques , mechanical removal, by hand removal, herbicides etc. Fully automated weed removal is very challenging as weeds have no uniformity either temporally or spatially on a field. This requires constant monitoring, detection and immediate response to weed growth else the yield is poor for the full crop cycle.

Selective spraying is now a well established technology with companies like Blue River with their computer vision and automated targeted spraying. Existing mechanical methods have been used between crop rows for decades for inter-row weeding. What is problematic however is detection of weeds amidst crops, with the advent of ML and RNN's the performance of the detection using either digital image data in the visible spectrum has improved significantly, approaching human level performance in ideal lighting conditions.

Performance reported using large image sets for training reaches upto 99% of weeds detected when there is no occlusion and in early stages of crop growth by Garcia-Ruiz et al.

In cases of heavy occlusion Dyrmann et al. proposed a method using CNN's on a dataset of 17000 weeds in images of winter wheat, they were able to achieve a performance of 47%.

Using other sensors such as the reflectance of spectra, Neural nets and SVM's were used by Karimi et al. to achieve detection rates of 69.2%

Using UV induced fluorescence measurement Longchamps et al were able to classify weeds with an accuracy of 91.8% under laboratory conditions. However this has not been tested in the field.

With the availability of large public data sets, this performance will only improve with time. Real time weed/crop detection has already reached extremely good performance levels that would make a large difference to crop yields if implemented using fully autonomous weeding systems that have the endurance and capability of scanning the field continuously.

2.3.2 Robotic system capabilities - Information gathering

While aerial platforms such as Helicopters with cameras or satellite imagery has been used extensively for data analysis, moving to a higher spatial resolution as well as exploring different angles has implications on the quality as well as type of data that can be gathered.

Proximal sensing is key to the enabling of precision agriculture. The types of sensors and sensor fusion based algorithms are rapidly evolving. However they broadly have similar requirements from the platform.

The ability to move rapidly to a location on the field and to provide a stable platform to enable the gathering of data.

Broadly the sensor types are to measure the physical characteristics of the plant. ie leaf area, plant height, etc.

Hyperspectral imaging in the near Infra red region that allows for the estimation of chlorophyll content of the leaves. Tucker(1979)

A set of specific wavelengths that enable the measurement of various components of the plant. ie: Nitrogen at 670nm-880nm Bronson et al. (2011)

Using thermal Infrared canopy temperature can be measure to determining the water stress of the plant as well as the water content in the canopy Seelig et al. (2008)

Camera data and modern ML algorithms also enable the tracking of yield as well as detailed leaf area and 3D structure of the plant. Ghozlen et al. (2010) Chene et al. (2012)

The fusion of this data will allow for high levels of optimisation of the crop yield and allow approaching peak technical efficiency of a field resulting in large cost savings.

2.4 Cable robots

Cable driven parallel robots are predicted to improve the performance compared to serial industrial robots by one to two orders of magnitude. As the IPAnema paper shows the performance of these systems are decoupled in the design space between the winch performance and the work volume. The dynamic as well as the payload performance of these robots are driven by the power of the actuator as well as from the chosen gearboxes. They are however size limited by the maximum tension of the cable chosen, the weight per length of the cable that will lead to sag under gravity and the requirement for never allowing negative tension along any of the cables determining the position of the robot.

The earliest work of cable driven parallel robots was a cable based Stewart's platform replacement called RoboCrane developed at NIST under a DARPA contract to stabilize loads carried by single point lifting devices such as cranes. This resulted in a 6 DoF cable suspended manipulator capable of millimeter level precision while being carried by another crane or equivalent for end applications. A work space size of 6m x 6m x 6m version of the RoboCrane was show to have accuracy of 1mm and .5 deg. It was also proven out in the initial prototype as well as payloads of upto 425 kg.

The ROBOCrane also demonstrated high lift to weight ratio and resistance to environmental perturbations as well due to the closed loop control system.

The ROBOCrane architecture is now being evaluated for tasks such as welding ship hulls where a 1 tonne welding platform will be transported across a ship dockyard and to replace Cartesian coordinate measuring machines for large objects.

Kurtz studied the problem of force distribution for cable robots in 1991 and proved that n+1 cables are required to fully constrain a rigid body with n degrees-of-freedom. Kawamura outlined first ideas of a seven cable parallel robot for teleoperation. At this time, Ming and Higuchi introduced a classification for cable robots to characterize different designs depending on the number of cables and degrees-of-freedom. It was experimentally shown that accelerations > 400 m/s2 can be generated by cable robots. Kawamura designed the Falcon system for fast pick-and-place operations to take advantages of outstanding dynamic capabilities of cable robots. Some years later, Tadokoro developed a mobile cable robot system for rescue after earthquakes and underlined the possibility to build a relatively light and portable robot.

The CABLEV system was designed to be a cable based crane for indoor warehouse applications and demonstrated feedback control purely on state and output variables and did not use positional information based on the length of the cables. It also showed that for under constrained cable robots small deviations can be compensated for with linear feedback as long as the dynamics of the system are captured upto the fourth order. Heyden - Woernle.

By changing the location of the drive we have a concept created by McDowell Douglas aerospace for space applications. It consists of a 8 motors and winches integrating into the platform that provides full 6 DOF with redundancy. The Concept shows high precision because of the high stiffness and lack of inertia. https://ntrs.nasa.gov/api/citations/199500172

A fundamental requirement for the RoboCrane is the requirement of fixed support points to enable control of rotational DoF's. Self-Contained Automated Construction Deposition System by Williams shows a version where the support structure can be built with a crank mechanism and 5 extra cables so the support structure required is also transported with RoboCrane style stewarts platform. The increase in complexity however allows for the RoboCrane to be fully independent with no requirements for rigid anchor points for their platforms. The authors use this capability to show the systems effectiveness in an automated construction use case.

A handling and assembly system for large-scale products, like collectors for concentrated solar power (CSP) plants, was studied by Pott.

The CABLAR system was developed by Bruckmann for automated storage and retrieval in warehouses.

Examples are presented to demonstrate simulated control including feedback linearization of the 4-cable robot (with one degree of actuation redundancy) performing a Cartesian task. As cables cannot transmit any compressive load, all solutions that involve a negative tension for positioning are invalid. Williams et al, provide a solution for keeping cable tensions positive and for reducing the amount of cable - cable interference.

Jaeung presented a six cable-based pose measurement device with its respective forward kinematics for 6-3 configuration with planar machine frame where both sagging of the cables and elastic elongation are addressed.

A more exotic approach was presented by Ghasemi who employed neural networks for forward kinematics to allow for feedback-less control, requiring no predesigned control model of the robot.

The state of cable robots is approaching maturity with both control models as well as potential practical applications.

Large area - Overhead Manipulator for access of fields or LOMAF was developed by Roger V Bostelman and Jeffrey W. White as a potential platform for high throughput phenotyping. They prototype an architecture closest to one being examined in this thesis. They base their platform on the original NIST robocrane and use the masts as a method to move the robocrane to the required location on the field. To examine the area of work versus the heights of the masts as well as the area covered by the platform to evaluate its potential as an agricultural phenotyping platform. They examine 3 cases in detail with 2 scale models that are manually controlled.

- Just the running cables that move the platform in translation of all 3 axis
- With the addition of "down-haul cables" that are used to control the pitch and roll of the platform with support from the running cables.
- With down-haul cables attached to every mast and provides full control for all six degrees of freedom.

They examine the work volume possible with these 3 cases and limit it based on the angle of the platform that in their view limit the potential of the platform for crop monitoring as the platform angle will determine the accuracy of the sensing equipment on board.

Given the extensive work on the dynamics and controls of such robots, the control system design is not a limiting factor. The key limits are the physical constraints of the tower height, max tension allowed in the cables and the weight per unit length of the cable itself.

Chapter 3

Methodology

3.1 Research Questions

To evaluate a new platform architecture one needs to examine the problem at a level of detail that will allow both the constraints and advantages of the new architecture to be compared against its alternatives. This will allow us to answer the following research questions

- Is the proposed architecture a more efficient alternative to the current dominant architecture (tractor)?
- Does the proposed architecture have any advantages over the dominant architecture in certain crop types or non dollar metrics?

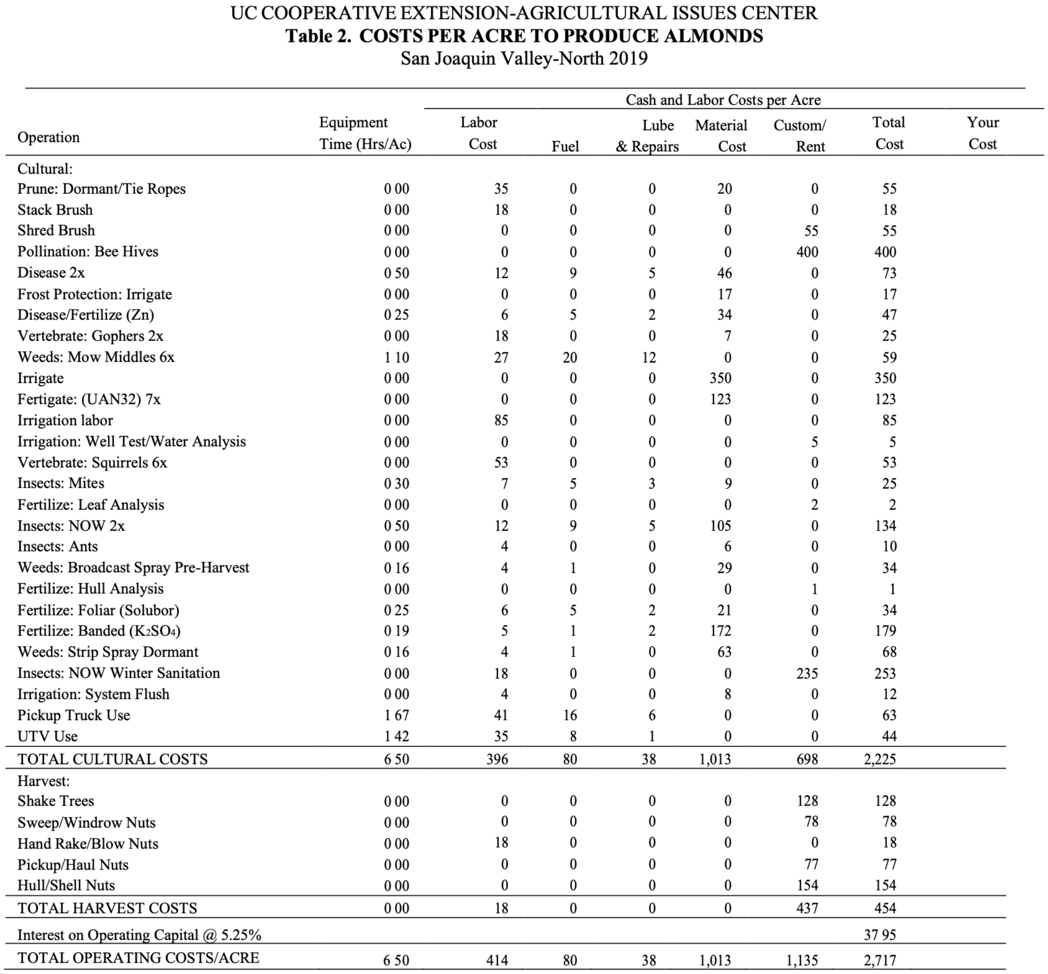
These two questions will allow us to fully characterise the cost, operational capabilities and limitations of the proposed system.

3.2 Defining the problem space

To be able to compare these systems in a close to real world simulation, we need real world data along with the latest in pricing / process and standard practice for a few crops that have different requirements.

UC Davis has been running cost studies to help farmers in California predict costs and revenue since the 1930's for a large number of crops. These studies can be found at coststudies.ucdavis.edu. They include the details of how many hours per acre a tractor is required and the various operations required over the full life cycle of the crop and the hours of human labor along with the skill level of the labor required.

This data set is ideal for our purpose, as it is at a sufficient level of detail to allow us to substitute the performance of standard operations with standard tools with predicted performance of the CableBot with a few different end effectors. An example table for almond production is show below.



UC COOPERATIVE EXTENSION-AGRICULTURAL ISSUES CENTER
Table 2. COSTS PER ACRE TO PRODUCE ALMONDS
San Joaquin Valley-North 2019

		Cash and Labor Costs per Acre						
Operation	Equipment Time (Hrs/Ac)	Labor Cost	Fuel	Lube & Repairs	Material Cost	Custom/ Rent	Total Cost	Your Cost
Cultural:								
Prune: Dormant/Tie Ropes	0 00	35	0	0	20	0	55	
Stack Brush	0 00	18	0	0	0	0	18	
Shred Brush	0 00	0	0	0	0	55	55	
Pollination: Bee Hives	0 00	0	0	0	0	400	400	
Disease 2x	0 50	12	9	5	46	0	73	
Frost Protection: Irrigate	0 00	0	0	0	17	0	17	
Disease/Fertilize (Zn)	0 25	6	5	2	34	0	47	
Vertebrate: Gophers 2x	0 00	18	0	0	7	0	25	
Weeds: Mow Middles 6x	1 10	27	20	12	0	0	59	
Irrigate	0 00	0	0	0	350	0	350	
Fertigate: (UAN32) 7x	0 00	0	0	0	123	0	123	
Irrigation labor	0 00	85	0	0	0	0	85	
Irrigation: Well Test/Water Analysis	0 00	0	0	0	0	5	5	
Vertebrate: Squirrels 6x	0 00	53	0	0	0	0	53	
Insects: Mites	0 30	7	5	3	9	0	25	
Fertilize: Leaf Analysis	0 00	0	0	0	0	2	2	
Insects: NOW 2x	0 50	12	9	5	105	0	134	
Insects: Ants	0 00	4	0	0	6	0	10	
Weeds: Broadcast Spray Pre-Harvest	0 16	4	1	0	29	0	34	
Fertilize: Hull Analysis	0 00	0	0	0	0	1	1	
Fertilize: Foliar (Solubor)	0 25	6	5	2	21	0	34	
Fertilize: Banded (K_2SO_4)	0 19	5	1	2	172	0	179	
Weeds: Strip Spray Dormant	0 16	4	1	0	63	0	68	
Insects: NOW Winter Sanitation	0 00	18	0	0	0	235	253	
Irrigation: System Flush	0 00	4	0	0	8	0	12	
Pickup Truck Use	1 67	41	16	6	0	0	63	
UTV Use	1 42	35	8	1	0	0	44	
TOTAL CULTURAL COSTS	6 50	396	80	38	1,013	698	2,225	
Harvest:								
Shake Trees	0 00	0	0	0	0	128	128	
Sweep/Windrow Nuts	0 00	0	0	0	0	78	78	
Hand Rake/Blow Nuts	0 00	18	0	0	0	0	18	
Pickup/Haul Nuts	0 00	0	0	0	0	77	77	
Hull/Shell Nuts	0 00	0	0	0	0	154	154	
TOTAL HARVEST COSTS	0 00	18	0	0	0	437	454	
Interest on Operating Capital @ 5.25%							37 95	
TOTAL OPERATING COSTS/ACRE	6 50	414	80	38	1,013	1,135	2,717	

Figure 3-1: Costs of almond production on an established orchard

To understand the system performance for a wide variety of crops, we selected

Almonds, Grapes, Romaine Lettuce, giving us one orchard crop, one vine crop with difficult access and a 70-130 day vegetable crop. In the established practice with tractors as the dominant architecture certain operations are only possible with human labor, for example the pruning of almond trees and similarly there will be operations that the new architecture will not be able to perform such as land leveling or pit digging. So the system evaluation will be a overall crop production cost evaluation and not just a cost evaluation of the machine hours required.

3.3 Performance estimation for CableBot

To get an estimate of the performance of the overall CableBot system, the modelling of three characteristics is required.

- Work-space volume: The length and width of the work-space are determined by the maximum cable tension allowable, the height of the towers supporting the cables and the number of towers. The maximum height required for a given crop will be a constraint on the lower bound.

- Number of movement operations per min: The winch motor dimensions and performance will determine the acceleration and velocity of the payload. A high torque low speed motor will allow for high wrench / payload performance with low routing performance, where as a high speed low torque motor will allow for high routing performance with low wrench and payload performance.

- Operation cycle time for end effectors: For continuous operations like spraying, the cycle time will be limited by the mass flow being delivered to the crop, however for discrete operations like harvesting the cycle time will be determined by the operating time of the end effector. Each operation to be performed will have an estimate of the cycle time based on the available literature and for operations that do not have end effectors fully developed an estimate will be used.

To determine the workspace volume we refer to work done previously while modelling cable parallel.

3.4 Tractor performance estimation

Tractor performance is required to estimate the number of hours of operation required to perform task on the field. This however is not required in our case as the costs and hour breakdown per acre is available in the UC davis cost studies. This allows for a direct NPV comparison without having to model the tractor performance in detail. As the data is recent, the performance of the tractors in the comparison is close to the best available.

3.5 Cost estimation for CableBot

The total cost of the system can be estimated based on the architectures key dimensions and the end effectors and sensors required to fulfill the operations of the required crops.

3.5.1 Cost breakdown

Structure

The structure consists of three main components, the columns to support the winches, the platform and cables. These are estimated as follows:

- Columns: The main load on the columns is the tension from the cable and the resulting bending moment. This bending moment is experienced in a 90 deg arc covering the entire work volume, this implies that I section columns are not ideal as they will not provide equal support in all angles, a tube cross section however is ideal . Hence the estimate is based on maximum bending moment allowable for the load required which gives us the required dimensions of the cross section. From these dimensions the mass multiplied by a production cost is used.

- Cables: The cable costs are estimated just using the length and the diameter of the cables to be used. The maximum tension allowable for a given cross section is used to determine the column stiffness required.
-

Motion and Control

The motion and control broadly have the cost of the compute element for control and the cost of the winches at each column.

- Compute: The cost of the compute element is common to all versions of the platform, this is based on the most commonly used platform currently for such applications which is called the Nvidia jetson series. This system is chosen as it has the best performance for ML based algorithms which is required by every robotic system operating in an unstructured environment.
- Motion: The cost of the winches is determined by the power of the motor and the maximum torque rating. As they are a standard industrial component these are sourced from vendor lists.

End effector and Sensors

The types of end effectors required vary with the operations required for the crop being analysed, however a common set of end effectors are required for the common operations on all crops. The sensor costs are based on the estimates in the literature for systems that can map, sense and navigate around the field.

- Robotic end effectors: End effector costs are driven mainly by the number of degrees of freedom required to perform the operation. These costs are estimated based on publicly available data and from papers describing these end effectors.

A lot of these systems have common vision, mapping and compute costs which are removed as the platform already contains those systems.

- Sensors: The types of sensors required are fixed for most agricultural robots, they have stereo vision for localisation, LIDAR for path planning and spectrometers that can operate in different wavelengths to capture the health of the plant. These costs are publicly available from electronic suppliers such as Mouser. The costs for encasement and ruggedisation is however estimated based on papers describing such systems.

Mass Input

Field mass input costs are identical to the prices given by the UC davis cost studies. If savings in mass required by the crop are achievable based on precision agriculture these are accounted for by reducing the quantity required.

Energy

The system is designed to be grid connected. Energy costs are calculated based on the time the system is in operation and the total power draw of the system. As the winches are the largest power consumer and the utilisation is much lower than 1, we estimate the usage by calculating cycle time for the operation and the percentage of the cycle time that is movement by the platform. The costs for compute, end effectors, sensing are estimated at .5 utilisation rate for the entire time the platform is in operation. This will give us the total energy consumed by the system. The average grid cost per unit of electricity for the years of the UC Davis cost studies are used to then calculate the energy costs for CableBot.

3.6 Cost estimation for Tractor

Tractor costs are driven by the power rating of the tractor and the level of automation that the tractor provides.

Capital Cost

The capital cost of a tractor is well understood and is accounted for in the UC Davis cost studies. The cost is determined by the power rating of the tractor and the level of automation if any.

Operating Cost

Operating cost of the tractor is fuel, maintenance and labor costs. These are also available in the UC Davis cost studies.

Chapter 4

Problem space model and evaluation metrics

The three crops selected represent a range of high human labor crop types, tree plantations, fruit plantations and short term vegetable crop.

For plantation crops, the cost of cultivation is split between the high initial setup costs for the first few years and the yearly operating costs of maintaining the plantation. The short term lettuce crop however has costs for the full cycle.

As the platform is not intended to do operations such as land leveling and pit digging, we choose to compare the costs only for the yearly operating costs for the plantation crops.

4.1 Almonds

Almond is a tree crop with a non yielding setup time of 3 years and where production is maximised from year 6 to about 1000kg per acre (approx 4000 m. sq). Tree density ranges from 75-180 trees per acre but the data we have is for 130 trees per acre which is what will be used.

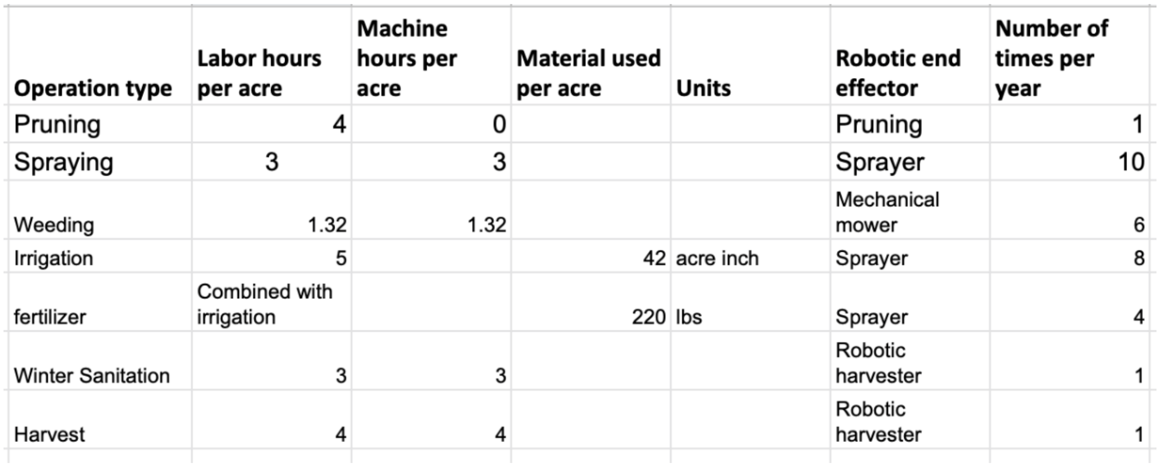
The tree spacing is 4.8m X 6.4m, this spacing includes space for access using trucks etc between rows. This could be reduced for the new system in a field optimised for CableBot but will not be considered in this case.

The operations required from year 4 are constant and consist of the following operations.

- Pruning
- Fertilization
- Irrigation
- Pollination
- Pest removal
- Harvesting Sanitation

Out of these operations only Pollination involves manual beehive introduction into the fields during flowering. The rest of the operations are a combination of human labor and equipment. To create a problem space where these can be compared, the operations are linked to the end effectors that can perform these operations with performance estimates.

A table is generated from the operations required with details.



Operation type	**Labor hours per acre**	**Machine hours per acre**	**Material used per acre**	**Units**	**Robotic end effector**	**Number of times per year**
Pruning	4	0			Pruning	1
Spraying	3	3			Sprayer	10
Weeding	1.32	1.32			Mechanical mower	6
Irrigation	5		42	acre inch	Sprayer	8
fertilizer	Combined with irrigation		220	lbs	Sprayer	4
Winter Sanitation	3	3			Robotic harvester	1
Harvest	4	4			Robotic harvester	1

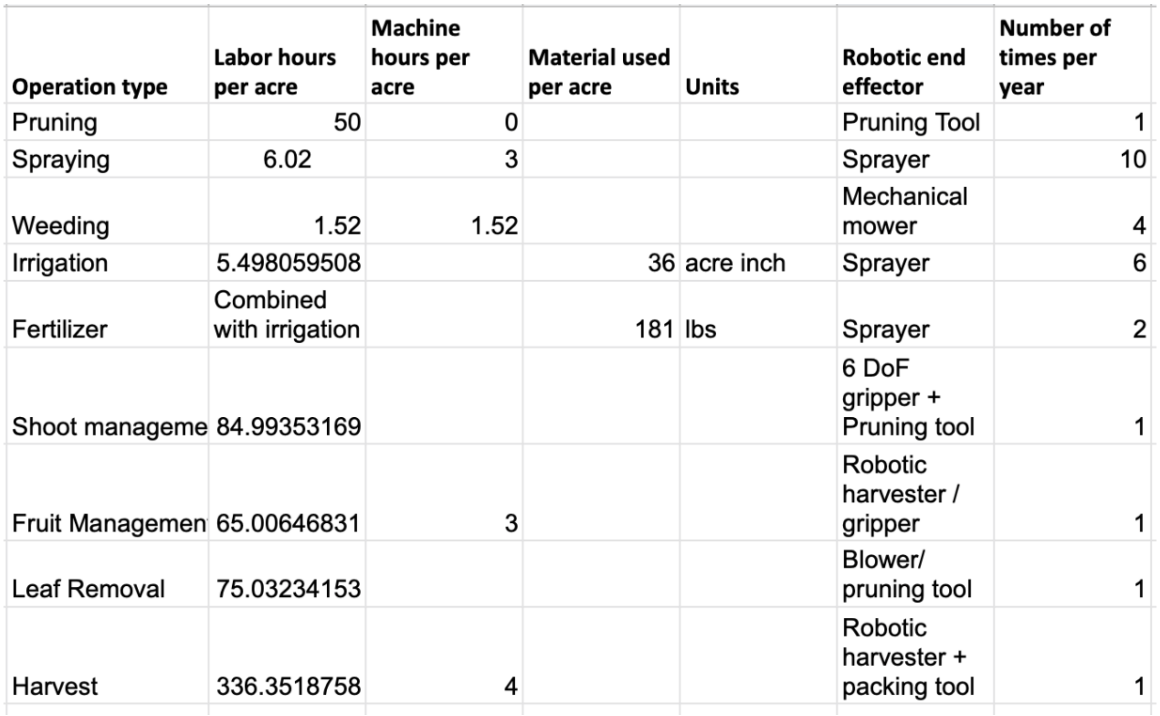
Figure 4-1: Operations for almond production

This table combined with the performance of robotic end effectors will give us the time required per acre for CableBot to perform the same operation.

4.2 Grapes

Similarly for a vineyard operation, there exists a large setup cost for the first 3 years and then a yearly production cost. Typically there are 605 vines per acre with a spacing of 2m X 4m. There is space between the vines for equipment access. The trellis structure for the vineyard is established before the initial planting is part of the setup cost. The production cost for grapes is dominated by manual labor with very little mechanisation. Certain operations such as vine repair, replanting of vines are not feasible using the CableBot platform, such operations are assumed to be still manually done and are not accounted for in the simplified problem space.

The operations table for grapes is given below.

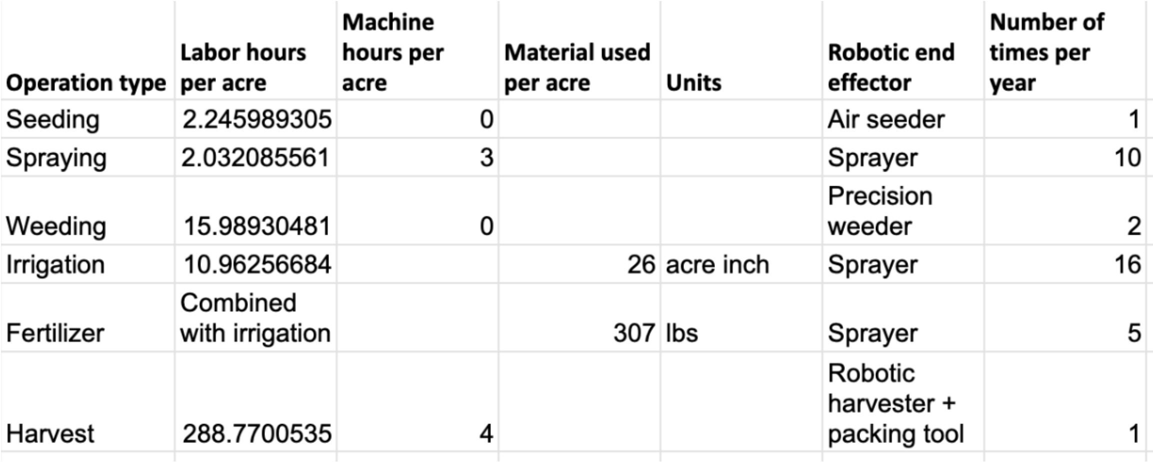


Operation type	**Labor hours per acre**	**Machine hours per acre**	**Material used per acre**	**Units**	**Robotic end effector**	**Number of times per year**
Pruning	50	0			Pruning Tool	1
Spraying	6.02	3			Sprayer	10
Weeding	1.52	1.52			Mechanical mower	4
Irrigation	5.498059508		36	acre inch	Sprayer	6
Fertilizer	Combined with irrigation		181	lbs	Sprayer	2
Shoot manageme	84.99353169				6 DoF gripper + Pruning tool	1
Fruit Managemen	65.00646831	3			Robotic harvester / gripper	1
Leaf Removal	75.03234153				Blower/ pruning tool	1
Harvest	336.3518758	4			Robotic harvester + packing tool	1

Figure 4-2: Operations for Grape

4.3 Lettuce

Lettuce is a short term vegetable crop that requires about approximately 100 days to mature from seed. Since the entire plant is harvested it requires planting with every harvest cycle. Land preparation is required every cycle as well with extensive tilling and leveling. The planting is done using an air planter which uses high velocity air to inject seeds into the prepared ground. The number of seeds per acre is extremely high initially at 189000 seeds per acre and is then thinned post 21 days to 20 cm spacing. The rest of the operations are standard except that harvesting is done by hand and is packed by hand as well. Two full crop cycles are possible in a year. The most labor intensive parts of the crop cycle is the hand weeding required as well as the harvesting and field packing process.



Operation type	Labor hours per acre	Machine hours per acre	Material used per acre	Units	Robotic end effector	Number of times per year
Seeding	2.245989305	0			Air seeder	1
Spraying	2.032085561	3			Sprayer	10
Weeding	15.98930481	0			Precision weeder	2
Irrigation	10.96256684		26	acre inch	Sprayer	16
Fertilizer	Combined with irrigation		307	lbs	Sprayer	5
Harvest	288.7700535	4			Robotic harvester + packing tool	1

Figure 4-3: Operations for Lettuce

4.4 Evaluation metrics

The simplified problem space model gives us the number of hours of labor required for the major operations that can be fully automated by the CableBot platform with either existing or near future end effectors.

The baseline production cost for each of these crops using existing state of the art methods is present in the UC Davis studies. There are certain operations that have been excluded for each crop type, the cost of these operations will remain the same for the CableBot System as well. Input costs for pesticides, fertilizers etc will be kept identical in the comparison as well. A case can be made to reduce these costs as precision agriculture will allow for the reduction of inputs required, but no extensive studies have been done to enable reliable estimates of the potential savings.

The capital cost of the CableBot platform will be calculated from the cost equation mentioned in Chapter 3. Based on the life of the platform a depreciation cost can be calculated and used to calculate the operating cost per year per acre. This would give us a reasonable comparison metric based on NPV for the farmer.

The Energy cost of these operations are another key metric to examine, given the focus on reducing the amount of GHG emissions from farming. The fuel and lubrication cost for tractors is provided with the approximate fuel price, this data can be used to then calculate the GHG emissions for a tractor dominated operation. For the CableBot system, the units of electricity will be calculated for the full crop cycle, this can be used to calculate the emissions based on the average emissions for the grid per unit of electricity generated.

Yield improvement can be another major factor for the comparison, however this requires extensive studies of precision agriculture data to enable an accurate estimation and will not be considered for analysis.

So the two metrics for evaluation will be the dollar Cost per Acre and the CO2 equivalent cost per Acre to cultivate the crop using the state of the art cultivation practices.

Chapter 5

Performance Model of CableBot

To estimate the operational performance of the CableBot platform we need to estimate the physical attributes of the platform.

5.1 WorkSpace Volume

The maximum distance between two support towers will determine the area of operation for a given maximum cable tension. $Vol = Area * Height$

Where, $Area = Distance^2$ and $Height = TowerHeight - MaxDroop$.

To simplify the calculation for droop and max distance between two towers we assume a uniformly loaded cable between two pillars.

For a given cable diameter the maximum allowable load will be $T_(max)$, this is a property of the cable selected and is known.

The total weight to be supported by the cables assuming a 4 tower CableBot is

$$Distance * Mass_{cable/m} * 2 + Mass_{Platform} + Mass_{Payload}$$

Using symmetry, this can be simplified to each pair of two towers supporting half the platform and payload mass.

So the new per length load will be

$$q = Mass_{cable/m} + \frac{(Mass_{Platform} + Mass_{Payload})}{2 * Distance}$$

To find the sag for a known tension T we get, vertical force at support R_y

$$R_y = q * Distance/2$$

The Horizontal Load R_x is,

$$R_x = \sqrt{T^2 - R_y^2}$$

The sag in the cable is then given by,

$$h = \frac{q * Distance^2}{8 * R_x}$$

The max height the platform can access is then given by

$$TowerHeight - h$$

For the Area calculation, the cable angle will be extremely high when the platform is at the boundaries of operation. A complex model was attempted but did not add value to the estimate. Broadly 5% of the border area is unusable due to the cable angles being greater than 45°. So the approximation that we will be using is

$$Area = Distance^2 * .95$$

5.2 Movement operations per min

The movement of the platform is determined by the forces generated by the winch motors and the inertia of the system.

At any given point the maximum force that can be exerted on the platform is given by the torque generated by a single winch.

Cables do not transfer compression and the 4 tower arrangement implies that the forces from the winches are split between the two horizontal directions.

Winch motor specifications are given by the maximum force or torque and the maximum velocity of the drum.

The typical operation sequence of the CableBot for start stop events is acceleration, steady state at max velocity then deceleration to stop.

For continuous operations it is acceleration, path following, deceleration to stop. In this case, the max velocity will determine the time taken to follow the path.

A lot of operations are stop-start where the platform is sent to a particular coordinate and held there until the end effector finishes the operation, followed by a new set of coordinates.

To estimate the time required requires us to estimate the time required for acceleration to max velocity.

As the winches are identical across all tower supports, the deceleration will be the same as the acceleration.

$$Time = \frac{MaxVelocity}{Acceleration}$$

$$Acceleration = a = Force/Mass$$

$$Force = Winchmax$$

$$Mass = CableMass * 2 + WinchInertia * 4 + PlatformMass + PayloadMass$$

5.3 Operation cycle time for end effectors

The time required for the end effectors that use the platform to perform the task is a key factor that will impact the systems performance. A reasonable estimate for most difficult operations such as grasping, cutting, harvesting is somewhere between 30-50% of human performance. For certain major operations we have better estimates from the literature.

5.3.1 Spraying

Spraying is one of the most important functions for the platform and is used for every function from irrigation to pesticides. The quantity to be sprayed can vary from a few milliliters aerosolised per plant to irrigation where it is measured in mm per acre.

Spraying performance is mainly determined based on the time it takes for the platform to recognise the object to be targeted. Going through various papers where ML recognition is done for precision agriculture, the typical cycle time is about 1 second. Certain companies like blueriver have managed to reduce that to about .5 seconds but that requires extensive optimisation for a specific usecase. The number of nozzles and the control of the nozzles are not a limiting factor in terms of the time required. This performance will improve with increase in compute power.

5.3.2 Harvesting

Harvesting cycle time is very crop specific as difficulty varies greatly. The typical cycle times for fruit recognition, path planning, grasping and retrieval is about 4-5 seconds which is what we use for grapes. Where as for something like lettuce harvesting, the cycle time is 31 seconds from the paper by Birell et all. Almonds pose a different challenge as the tree shaking mechanism is extremely efficient and can harvest from the entire tree in about 15 seconds with a custom machine. Almond trees require sanitation after the season as a certain pest will nest in unharvested shells and cause the yield of next years crop to fail. Other operations are similar to harvesting such as the tipping of grapes and pruning of the vines and branches.

The cycle time estimates are of lab based systems and are not tested at scale. These systems however are showing rapid improvement due to advances in ML and machine vision.

5.3.3 Pruning and vegetation management

Pruning and removal of unwanted vegetation on the crop is a very challenging operation as the decision making process on which vegetation to remove requires decision making that is complex and subjective. Tools to prune are also relatively dangerous compared to a gripper etc. This poses the additional challenge of safety in an environment that is not sealed away from humans. The literature gives us a cycle time of about 6 seconds for a grape pruning robot with a milling router as the end effector, with an average of 8.4 operations per vine.

Deweeding in between crop rows is a simpler operation and can be done as a continuous operation with purely mechanical means.

Zahid et all show the operation of a tree pruning robot with cycle times of about 10 seconds per cut and about 15 cuts per tree.

These are the three major operations that are required to estimate the performance of the CableBot system.

Chapter 6

Results and Discussion

6.1 Results

Implementing the performance model in Matlab, we run about 30,000 simulations while varying the design variables of cable type, tower height, distance between towers and payload capacity.

This gives us the maximum height based on the sag and Area covered by the CableBot system for the DoE. We find that a significant number of solutions have negative max height, which makes these solutions invalid. We eliminate these from the solution space.

We also find solutions where the max force exerted by the winch exceeds the max tension allowable. We remove these from the extended solution set as well. We are then left with approximately 70000 feasible designs that are then used to calculate the performance in the problem space.

This gives us the following metrics, such as the total capital cost vs the amount of area covered by the system. Shown below

Though the performance model was evaluated the problem space model for all three crops could not be evaluated completely, this is due to the code requiring a lot of computation time and could not be validated.

We found that though the capital cost of the system was far greater than a tractor, the amount of labor cost saved made the system economically feasible at certain

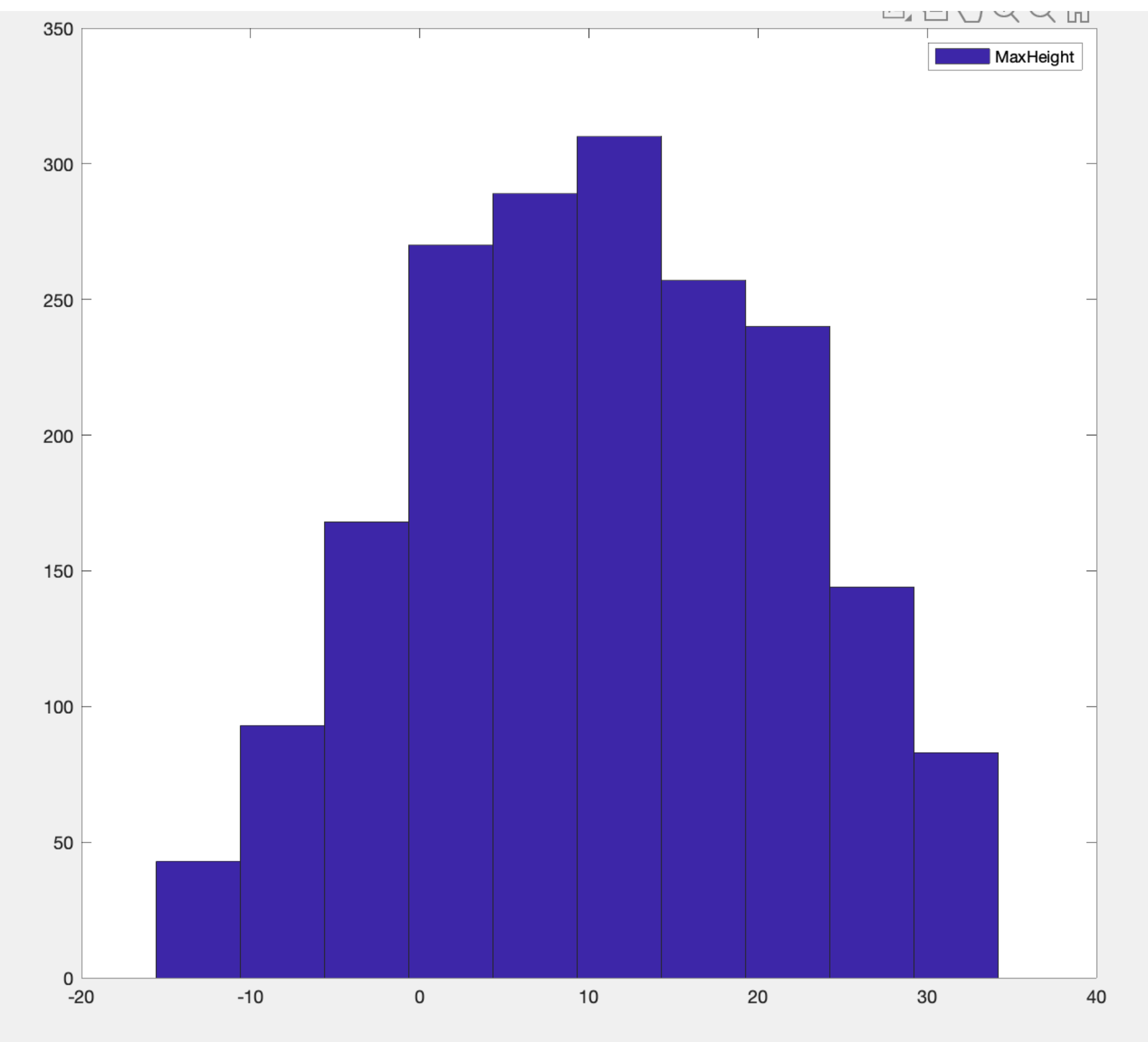


Figure 6-1: Histogram showing Max height of work volume for CableBot

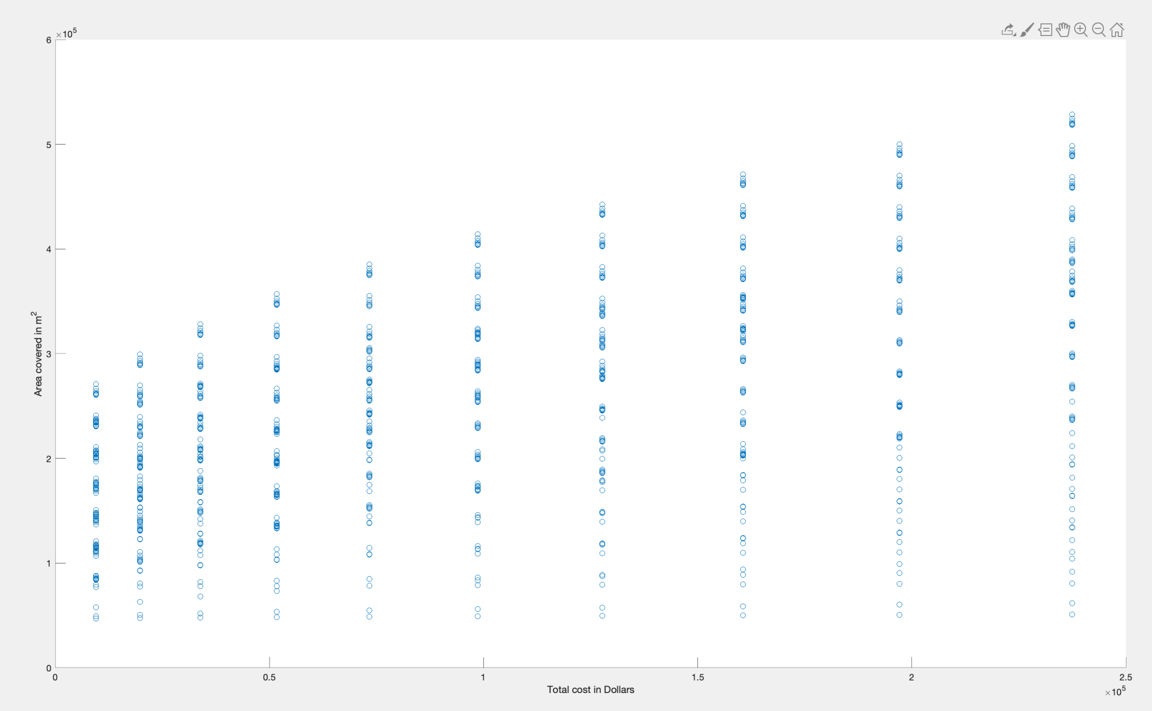


Figure 6-2: Total Capital cost of the system vs area covered

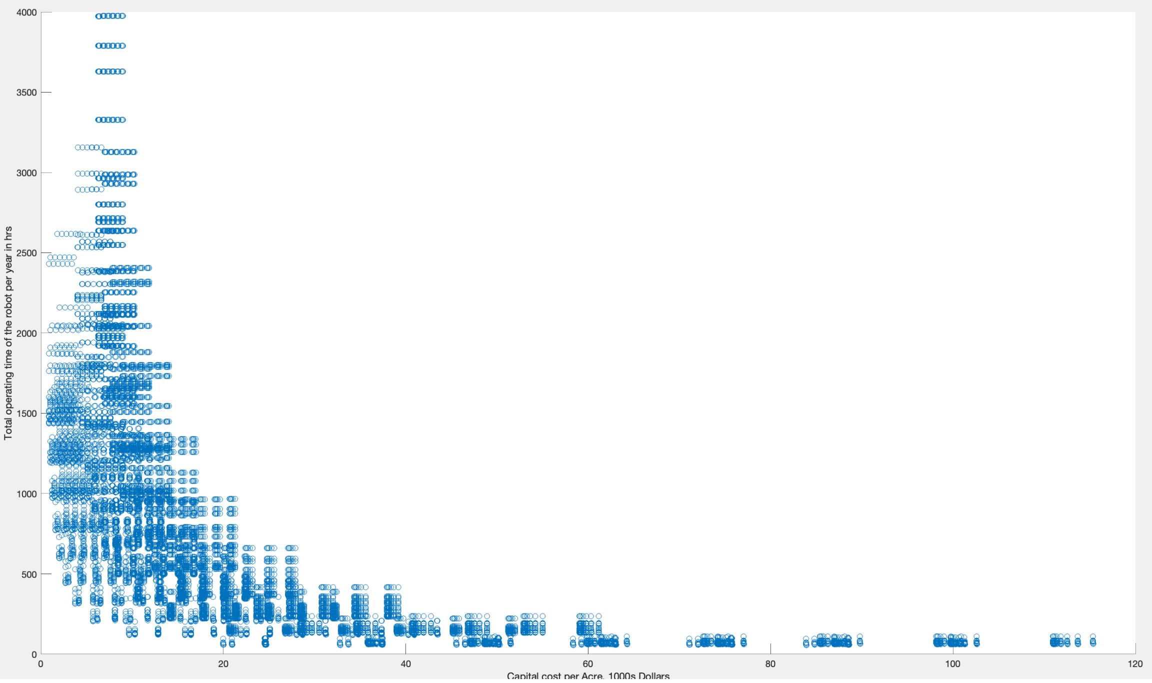


Figure 6-3: Cost per acre vs Total time required for almond crop cycle

scales. The system also has a very high utilisation rate, this implies that additional operations required by precision agriculture may not be feasible. We also found that for high labor intensive crops the system does outperform the dominant architecture.

We also find that the new method to compare the new class of agri robotics in the context of high value crops with high labor requirements.

While the research was not complete as designed, a systems approach does show merit for consideration for introduction of new technology into agriculture.

6.2 Conclusions

This thesis examines a potential new architecture for Agri-robotics. A series of architectural decisions are examined and evaluated against a pre-populated problem space foccusing on labour intensive high value crops. The evaluation also consists of performance metrics at an L1 level and evaluation of the solution space using methods from MDO. The architecture is then compared to existing dominant alternative and future work is suggested.

We examined the new architecture for productivity, energy usage, and cost.We also developed a novel method to examine the productivity, cost and potential for agri-robotic systems.

The potential to evolve the CableBot design by examining other critical architectural decisions exist from including multiple platforms. A lot of assumptions were made while examining the architecture and a higher fidelity model would be useful. A model that can account for platform features to examine where the maximum value can be found would be useful.

Future work could include examining the ability to change tools automatically, expanding the crop types that can be examined, and the examining the systemic effects. We also did not explore the potential cost savings of reducing input requirements based on the precision agriculture possible on this platform.

Appendix A

Code

The following code runs a Design of experiments on the solution space of CableBot

TowerH = linspace(5,30,10) dist = linspace(100,500,40) Payload = linspace(20,120,10) Winch = zeros(5,2) Rx = 0 tau = [] cnt = 0 MaxHeight = 0 Area = 0 for i = 1:length(cablespec) for j = 1:length(TowerH) for k = 1:length(Payload) for z = 1:length(dist) cnt = cnt+1; [cablespec(i),TowerH(j),Payload(k),dist(z)];

CableMass = dist(z)*cablespec(i,2)/2; TotalMass = CableMass + (Payload(k)/2); q = TotalMass/(dist(z)/2); Ry = TotalMass; Rx = sqrt(cablespec(i,1)$^2 - Ry^2); sag(cnt) = q \ast dist(z)^2/(8 \ast Rx); MaxHeight(cnt) = TowerH(j) - sag(cnt)$;

Area(cnt) = dist(z)$^2 \ast .95; StructInertia(cnt) = Inputvariables(cnt, 1 : 6) = [cablespec(i), TowerH(j), Payload(k), dist(z), MaxHeight(cnt), Area(cnt)]$;

end end end end

The code below defines the problem space for Almonds as a crop.

acre = 4046

Plantsperacre = 130; plantsperm2= 130/acre; diag = sqrt(4.8^2+6.4^2)$; b = 4.8; h = 6.4; pruningpertree = 10 * 15; harvestingpertree = 2 * 250; SanitationTime = 2 * 10; Spraying = 3600*3; numberofsprayingoperations = 10; Irrigation = 8+4; fori = 1 : length(Inputvariables)$

Acceltime = Inputvariables(i,10)/Inputvariables(i,9); PathLengthper$_m$2 $= (100/b)* 100/10000; ContinuosTravelTime = PathLengthper_m2*Inputvariables(i,6)/Inputvariables(i,10)+ (PathLengthper_m2*Inputvariables(i,6)*Acceltime*2/Inputvariables(i,4)); PerPlantTravelTime = Inputvariables(i,6)/acre*Plantsperacre*Acceltime*2; Weeding = ContinuosTravelTime; Pruning$ $pruningpertree*Inputvariables(i,6)*plantsperm2+PerPlantTravelTime; Irrigation = ContinuosTravelTime; Sanitation = SanitationTime*Inputvariables(i,6)*plantsperm2+ PerPlantTravelTime; Harvesting = harvestingpertree*Inputvariables(i,6)*plantsperm2+ PerPlantTravelTime;$

TotalTime(i) = Harvesting+Irrigation*12+Sanitation+Pruning+Weeding*6; TotalEnergy(i) = (TotalTime(i)*.3*Inputvariables(i,13)*1000+2000*TotalTime(i)*floor(EndEffectorCost

The following code performs cost calculations for the system as well as the energy calculations

E = 210e9; beamcost = 0; Totalcost = 0; for y = 1:length(Inputvariables) h= Inputvariables(y,2); f= Inputvariables(y,8); del = h/360; m = f*h$^3; d(y) = (m/(3 * E * del * .3439))^1/4; beamcost(y) = (3.14 * (d(y)^2 - (.9 * d(y))^2)) * h * 7850 * 2.25;$

CableCost(y) = Inputvariables(y,1)/30e6*Inputvariables(y,4)*2*998*20; WinchCost(y) = Inputvariables(y,12)*4; ControlsCost =499*2; SensorCost = 5000; EndEffectorCost(y) = floor(Inputvariables(y,3)/20) * 30000 + 10000; TotalCost(y) = beamcost(y) + CableCost(y)+ WinchCost(y) + ControlsCost + SensorCost + EndEffectorCost(y); CapCostperAcre(y) = TotalCost(y)*4046/Inputvariables(y,6); end

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