

## ABSTRACT

EDENHART-PEPE, SKYLER. Aerial Scouting of Agricultural Fields: Theory and Implementation using Mobile Battery Exchange Stations (Under the direction of Dr. Lawrence Silverberg).

Unmanned aerial vehicles are offering new opportunities in different industries but have not yet been widely adopted in agriculture. Visual acuity in agricultural scouting naturally divides into identifying whether or not a plant is healthy and, if not, diagnosing the problem. In this thesis, I correspondingly divide crop scouting into aerial and walking (two-stage scouting) and suggest that this division of responsibility has the potential of significantly lowering the cost of crop scouting. Moreover, two-stage scouting can be performed today. Looking ahead, aerial scouting can be further advanced through the use of mobile battery exchange (MbeX) systems, to make on-demand data acquisition possible. Toward this end, this thesis investigated two-stage scouting and designed and developed an MbeX system. The methodology developed in the thesis began with defining a walking reduction measure, recognizing that the savings from aerial use is derived from the percentage of the field that potentially needs human inspection (which depends on the application). The thesis shows that two-stage scouting requires less labor than walking-alone scouting by 230% in a representative scenario, and that the MbeX provides an additional savings of 11%, and moreover, can serve as a gateway to implementing a lot of use-cases for agriculture.

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Aerial Scouting of Agricultural Fields: Current and Future Practices

by  
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## **BIOGRAPHY**

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## TABLE OF CONTENTS

<b>LIST OF TABLES</b> .....	v
<b>LIST OF FIGURES</b> .....	vi
<b>Chapter 1: Introduction</b> .....	1
<b>Chapter 2: Method</b> .....	4
2.1 Method of two-stage scouting.....	6
2.2 Method of MbeX.....	9
2.3 Aircraft alignment.....	10
2.4 Battery exchange.....	12
2.5 Control hardware.....	13
2.6 Exchange sequence .....	14
2.7 Monetization .....	15
<b>Chapter 3: Results</b> .....	16
3.1 Performance .....	17
3.2 Flight test experiment design .....	34
3.3 Failure/Reparability .....	20
3.4 Digital farm feasibility .....	22
<b>Chapter 4: Summary/Conclusions</b> .....	24
<b>REFERENCES</b> .....	26
<b>APPENDICES</b> .....	29

## LIST OF TABLES

Table 1. Parameters for Scouting N fields .....	7
Table 2. Flight Performance.....	33
Table 3. MbeX Complexity .....	21
Table 4. Hours spent to develop the proof-of-concept MbeX .....	23

## LIST OF FIGURES

Figure 1.Scouting approaches .....	5
Figure 2.Scouting N fields .....	8
Figure 3. 3D Model of battery exchange system .....	10
Figure 4. Aligning and securing the aircraft .....	11
Figure 5. Battery exchange mechanism .....	12
Figure 6. Electrical box .....	13
Figure 7. Supply Chain .....	15
Figure 8. Power Supply.....	31
Figure 9. Time to Walk N Fields .....	18
Figure 10. Time to Fly N Fields versus Field Size .....	19
Figure 11. Battery Enclosures .....	32
Figure 12. Flight #1: Waypoint camera trigger and cameras showing GSD .....	35
Figure 13. Flight #2: Waypoint camera trigger and cameras showing GSD .....	36



## Introduction

Scouting of agricultural fields by unmanned aerial vehicles is being considered throughout the world. Much of the focus in precision agriculture research using aerial platforms is consistent with acquisition of data for advancements in plant and crop health assessments. For example, unmanned aerial vehicle (UAV) data can already identify nitrogen levels with miniaturized remote sensing cameras and more such advancements are sure to follow [1, 2]. Capitalizing on main advantages of UAV's, traditional high altitude observations are no longer required in some applications requiring advanced sampling techniques. Modest advancements in satellite remote sensing with daily coverage of 1-2 meter resolution is not sufficiently fine for specific use cases which makes a strong argument for the use of UAV's. For example, Conservation studies are using UAVs in the location of wildlife species. UAVs capture photos and video as an inexpensive and timely alternative to satellite and manned aircraft surveillance for estimating species population size. Considering environmental changes, species decline, or invasive species introduction, the value of harnessing technology for the collection of unprecedented amounts of data is today more evident than ever. [3]. Growing interest UAVs is reflected in hundreds of research articles published over the past 25 years.

Applications in forestry also capitalize on the flexibility of the UAV platforms. Issues prompted by human activity which require rapid scouting can be responded to promptly for the acquisition of critical data. A task where High-resolution imagery is essential to monitor aspects of the 'stand' in forestry, forms of data acquisition other than UAV are unsuitable for a variety of reasons [4, 5]. UAV's are even seen to complement ground surveys in communities where access to walking forest scouting is unavailable due to dangerous conditions. Similar to forestry, geomatics has begun adopting UAV technology by conducting low budget research using the photogrammetric 'structure-for-motion' method for high resolution topographic reconstruction. At the base level of analysis, aerial data collection by a UAV in poor accessibility areas for terrestrial photogrammetry represents a viable alternative to manual surveying and demonstrates, "an apparent logistical advantage" [6-8] to other methods.

While advantages are clear, there are numerous challenges confronting the implementation of UAV technology in agricultural applications including; cohesive data management and analysis

for the expansive amount of data that can be collected. For ‘deep learning’ to occur with big agricultural data requires that remote sensing data be used “to address... the complex, multivariate and unpredictable agricultural ecosystems by monitoring, measuring and analyzing continuously various physical aspects and phenomena.” [9].

Current practices in agricultural require labor intensive crop scouting in the initial visual assessment of the crop. Crop scouts often walk through fields in various patterns to visually inspect plant health and extent of pest infestation. Based off these visual inspections, economic decisions are made relating to the application of pesticide, nutrients, or herbicide to the crop. The farming community must be convinced of the short and long-term benefit of UAVs as a data acquisition tool. Unfortunately, “best practice workflows for producing high-quality remote sensing products from UAVs are still lacking. Further studies that focus on validating UAV-collected measurements with robust processing methods are important for improving the final quality of the processed data” [11] and for influencing the adoption of UAV technology. The effectiveness of the application of on-site operated UAVs in commercial agriculture has not yet been realized. The potential value of operator-free UAV technology for agricultural applications is recognized but not fully understood. For example, the operator-free UAV is remotely operated and would function as a field scout that, “If successfully integrated and implemented...could play a key role in increasing productivity, quality, and reducing production cost, enabling customized plant and crop treatments.” [13] In a recent study from the Centre for Automation and Robotics, integrating autonomous aerial surveillance with ground-truthing is explored. They argue that, “The proper integration of aerial and ground units would make use of the current autonomous robots more efficient for treating environmental disasters...Such integration could be applied even in agriculture, where some agricultural tasks, such as weed treatment, might be accomplished by ground units only in the affected zones by following a weed distribution map obtained from the information provided by the aerial units.” [14]. Linking an autonomous scouting step with an autonomous treatment step has been studied and findings reveal that, “an autonomous and heterogeneous fleet to implement the entire process autonomously and accurately” can be used effectively [14]. If effective use requires adoption than a re-evaluation of the fundamental operations of crop scouting logistics must be made. One of the limiting factors in adopting the widespread use of this tool is the challenge of extracting meaningful and actionable information

from data collected via UAV remote sensing. There is an immediate need to develop methods to perform tasks such as scouting for all types of agricultural operations [12].

Very few agricultural fields are scouted by unmanned aerial vehicles despite progress being made in advancing technological solutions. The hypothesis of this thesis is that a major reason for the lack of adoption is the superiority of visual acuity through traditional walking over fields. Additionally, this thesis proposes that there is a need to distinguish between the question of whether or not a plant is healthy and the question of the cause of a plant's unhealthiness. This distinction is related to visual acuity because crop consultants and personal experience tell suggest that the level of visual acuity required to determine whether or not a plant is healthy is much lower than the level of acuity required to determine a cause of a plant's unhealthiness. The former does not require any action and is preliminary whereas the latter requires action based on best practices that can be quite involved and involve cues that extend beyond visual acuity. Indeed, when a plant is healthy, it has grown to a healthy size and has healthy coloration that is easily apparent upon observation. The difficulties exist when there is a deviation from a normal plant size and coloring. So, what is the implication to the scouting of agricultural fields by unmanned aerial vehicles?

There are a variety of other platforms recently studied and developed to extend flight and operation time that have been tested with limited success in facilitating the use of these platforms commercially. For example, a wireless charging method to recharge the battery of a drone has been used with the focus on efficiency in the energy transfer process rather than mechanical exchange of the batteries. [16, 17]. Kemper et al studied the economic feasibility of two competing design concepts at a high level and then employed design methodology to develop a sufficient platform based on key ideas/features. These key idea/features were, "modularity, orientation independence, terminal connections and matching, cost effectiveness and complexity" [18]. Even automated ground service stations such as the platform designed at the MIT Aerospace Controls Laboratory included successful autonomous landing and recharge for multirotor UAVs [19, 20] but didn't make the link between design and end user. Proposed solutions and those which would benefit smart agriculture have unique advantages in the data acquisition process allowing more feasible science to be conducted. Zhang et al notes "The limitations identified for applications of remote sensing systems in farm management include: the collection and delivery of images in a timely manner, the lack of high spatial resolution data, image interpretation and data extraction issues; and, the integration of these data with agronomic data into expert systems (Jackson

1984;Du et al. 2008).” Opportunities remain for the implementation of mobile battery exchange stations in agriculture but not without several barriers – one of which is cost. In agriculture, predominant labor driven costs are offset in this new form of ‘on-demand’ data access. Implementation of the MbeX and advancements of the technology will cost more initially but ultimately reduce costs long term.

In the method section both research questions are considered. The results section gives illustrative examples and describes an MbeX fabricated to look at the second research question and how remote access at the field can be automated at different levels. The paper ends with a summary and helps answer the question of how this can be used today and in the future.

## **Method**

In this thesis, the unmanned aerial vehicle is tasked with “course-scouting.” The objective of the course-scouting is to determine whether or not plants in a field are healthy. The objective is *not* to ascertain more information than that, for example, to determine a cause behind any deviations from normal plant sizes and coloring. Since the scouting is being performed by an unmanned aerial vehicle, this stage will be referred to as aerial scouting. The aerial scouting is followed by “fine-scouting” that is performed by a crop consultant or the like who walks the field. This second stage is called walking scouting.

This thesis addresses two questions. *The first question is whether and to what degree is two-stage scouting more efficient than walking scouting?* Of course, the question of the feasibility of this two-stage scouting approach is *not* to improve crop health over existing methodologies but to determine whether there is any efficiency gained, that is, any cost savings in two-stage scouting over walking scouting alone. If there is, two-stage scouting could offer farmers (the employers) a cost benefit. Additionally, it could open up future possibilities of using unmanned aerial vehicles to improve crop health, since the unmanned vehicles are already in their hands.

The second question that this thesis addresses goes further with the course-scouting stage. Currently, during a season, a field may be scouted on a regular basis, sometimes daily and often weekly, to ensure crop health. Much of the scouting could be unnecessary, i.e., walking may be

performed with the outcome as crops are healthy – a task that course-scouting can perform. Furthermore, in many fields, just traveling out to them can be time consuming. Farmers often own large numbers of non-contiguous farms, often in remote locations, so getting out to them is proportionally significant. Operating a system remotely to acquire data on demand establishes a new capability for data access in agricultural fields which is the basis for the second question. *Whether and to what degree is the operator-free UAV more efficient than the on-site operated UAV?*

This thesis considers two methods for course-scouting. The first method considered is how aerial & walking scouting compares with walking scouting. The second method considered is how MbeX aerial scouting & walking scouting compare with aerial & walking scouting (without MbeX). Below, we begin with the first question and then address the second (See Figure 1). The first question is addressed by looking at differences in labor costs. The second question is about the feasibility of an MbeX system and the cost savings it provides.

<b>Walking</b>	<b>Aerial &amp; Walking</b>	<b>Aerial MbeX &amp; Walking</b>
Both course scouting and fine scouting are achieved by walking.	<ol style="list-style-type: none"> <li>1. Course scouting achieved by on-site operated aerial vehicles</li> <li>2. Fine scouting achieved by walking.</li> </ol>	<ol style="list-style-type: none"> <li>1. Course scouting achieved by operator-free aerial vehicles</li> <li>2. Fine scouting achieved by walking</li> </ol>

Figure 1: Scouting Approaches.

Finally, this thesis recognizes that two-stage scouting, in the absence of an MbeX, imposes on the crop consultant an aerial vehicle ownership requirement. The ownership requirement consists of investing in aerial vehicles, in maintaining them, and in training their agricultural

technicians in their operation. Furthermore, it is recognized that the crop consultant would prefer leasing MbeX systems than owning them. If such leasing entities were available and the leasing costs were acceptable, the benefits of specialization would be realized. Specifically, benefits would be seen due to the relaxation of required investments such as maintenance, training, and operation. The leasing possibility, although not yet available, is a disruptive scenario that would monetize the MbeX and then the digital farm. This section ends with a description of the supply chain that monetizes the MbeX.

## 2.1 Method of two-stage scouting

The potential advantage of this approach over the traditional walk-only approach depends largely on a walking reduction measure, that is, the degree to which the aerial inspection in the first stage reduces that amount of walking necessary at the second stage. Based on structured, face-to-face interviews conducted with four crop consultants in North Carolina and two in Minnesota, expected walking reduction measures of 15% to 25% are reasonable. Denoting the walking measure by  $\Omega$ ,  $\Omega = 10\%$  corresponds to a need to walk 10% of a given field. The parameters in the problem are given in Table 1.

Table 1: Parameters for Scouting  $N$  fields.

---

$A$	Area scouted per hour either by walking or by unmanned aerial vehicle (acres/hr)
$S$	Area of a field (acres)
$T_{field}$	Time to scout an entire field (days)
$T_{travel}$	Time to travel from field to field (days)
$T_{days}$	Number of work hours in a day (hours)
$N$	Number of fields
$n_{days}$	Number of days to complete the job (scout $N$ fields)
$n_f$	Running time toward completing a field (internal variable)
$dT$	Running time increment (internal variable)
$T_d$	Running time toward completing a day's work (internal variable)

---

With these parameters, an algorithm was developed that determines the number of days  $n_{days}$  required to complete the scouting of  $N$  fields. The flow chart of the algorithm is given in Fig. 2. First, note that the problem is defined by 5 parameters (the first 5 parameters in Table 1) and by 3 internal variables (the last 3 parameters in Table 1). Next, note that the algorithm loops in time, in increments of  $dT$ , and ends when the scouting of all of the fields has been completed.  $T_d$  is updated when beginning a new day and  $T_f$  is updated when completing a field. When the running time in the day exceeds the running time toward completing a day's work, we reset the running time of the day to 0 (but have not yet increased the number of days). When the running time to complete a field exceeds the time to complete a field, the number of fields completed is increased by 1 and the running time to complete a field is reset to 0. Finally, notice that travel to another field is not made in a given day when the time left in the day is less than twice the travel time to the next field.

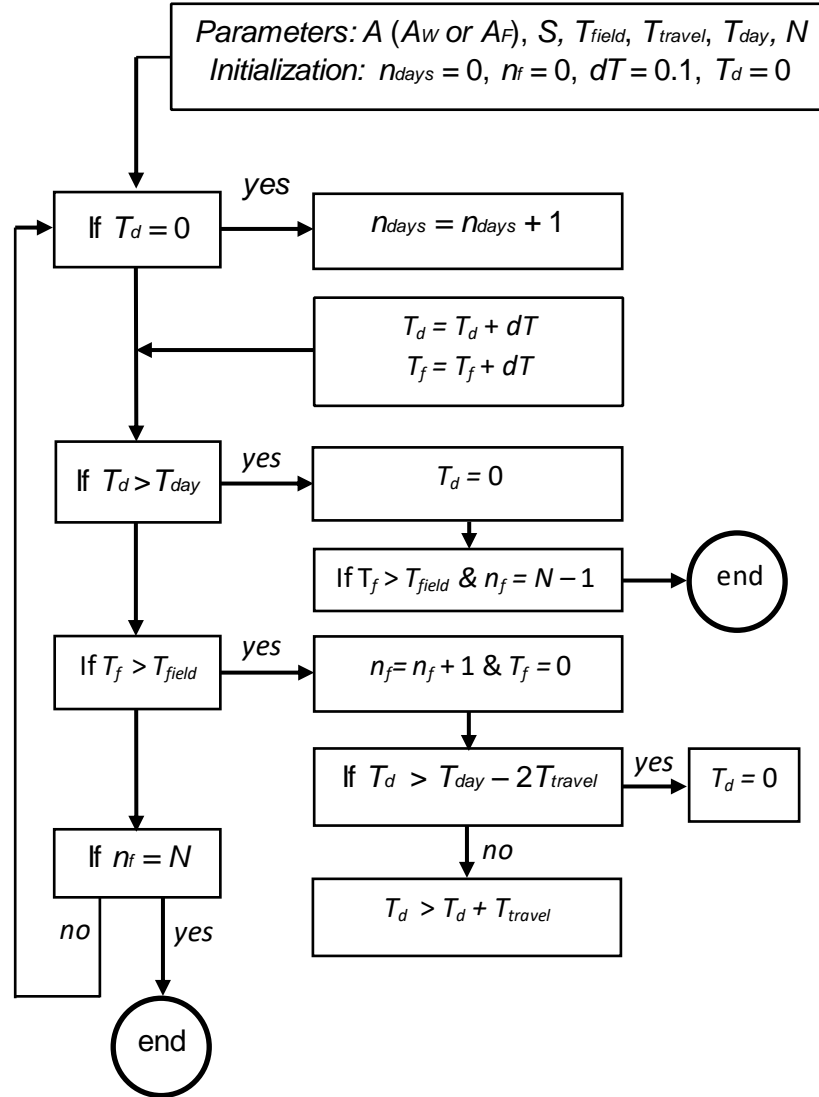


Figure 2: Scouting  $N$  fields.

This flowchart can be used to determine the number of days required to complete scouting  $N$  fields, whether scouting by walking or by a UAV. The trade-off between walking and scouting, determined on the basis of this algorithm, is given in the results section. Of course, once the number of days to complete the scouting of  $N$  fields is determined, it becomes a simple matter to determine the labor costs of the scouting scenarios.

One last consideration that arises in aerial scouting is the processing time associated with the images. Real-time video could be employed to eliminate processing time, whether or not the scouting is in real time. However, this can be technologically challenging depending on the



location of the field and aerial obstacles. A technologically simpler option that is currently more widely used is to stitch the images together. The processing time is a function of the level of stitching being performed, the number of images, the percentage of overlap in the images, etc. Holding the other parameters constant, processing time is, for the most part, linearly proportional to the number of images (which depend on vehicle altitude and percentage of overlap). Holding the other parameters constant, processing time to stitch images is given by  $T_p = NS/(AT_{days})$  in days (for the purposes of the results section).

## 2.2 Method of MbeX

Aerial inspection can go one step further by automating aerial vehicle take-off and landing, accomplished by a battery exchange station. This can not only reduce labor needs but, perhaps more importantly, reduce time consumption. In the areas in which the fields are moderate in size and separated from one another, a battery exchange station can nearly eliminate travel time. In areas in which the fields are large, battery exchange stations can significantly reduce the time to monitor a whole field. However, it should be noted that maintenance and repair of battery exchange stations necessitates that they be mobile. Ultimately, whether or not an aerial system employs a battery exchange system, the advantages gained by using UAVs when employing the proposed strategy, will depend on the walking reduction measure.

In the remainder of this section, the components of a mobile battery exchange (MbeX) system are considered in some detail. The MbeX placed 2<sup>nd</sup> in the Land-of-Lakes Challenge, a worldwide UAV competition whose mission was to advance drone technology applied to agriculture.

Ultimately, the mobile battery exchange system enables continuous aircraft operation in a cost-effective manner in terms of maintenance and repair. Figure 3 shows the subsystems: a landing platform for the aircraft, a battery exchange mechanism with X-axis, Y-axis, and Z-axis control, and a bay station of flight batteries. Control hardware (shown later) controls the motion of the landing platform and of the battery exchange mechanism. The method section describes these subsystems along with the power system, performance requirements, and operations. For

simplicity, the systems was kept to five motors, 3 limit switches, 3 proximity sensors, and one ultrasonic sensor, as further explain in this section.

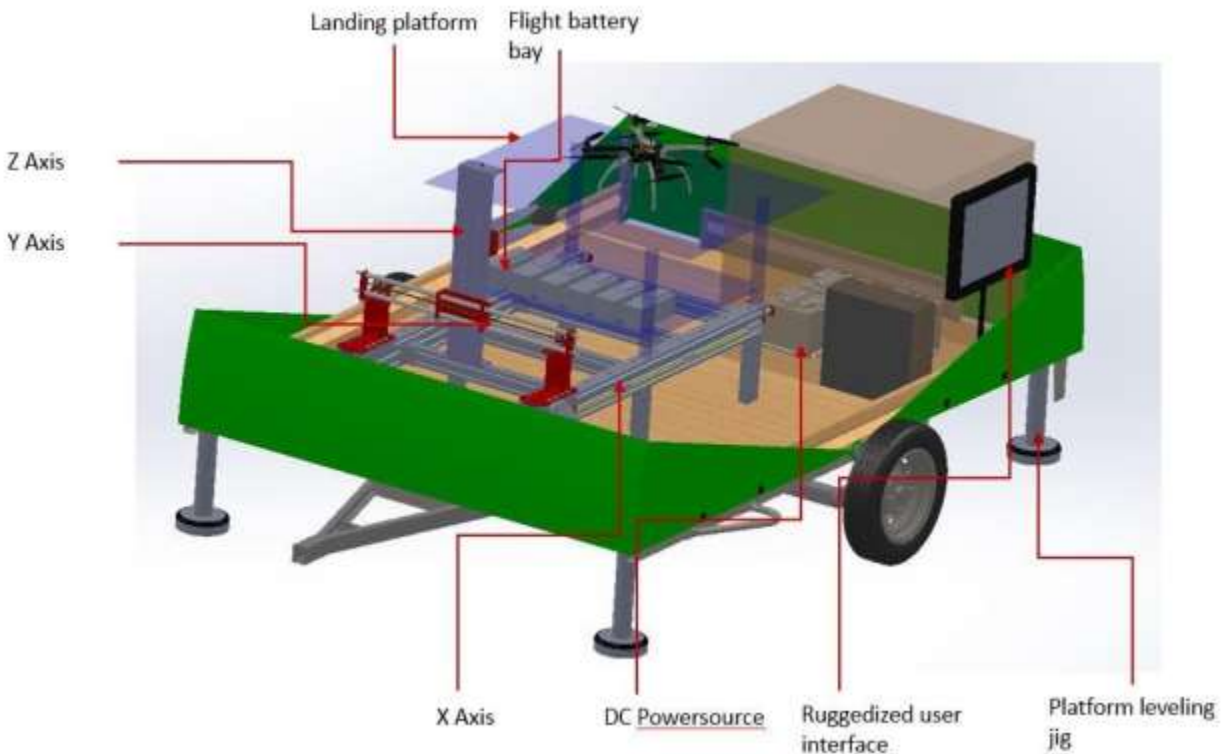


Figure 3: 3D model of the mobile battery exchange system.

### 2.3 Aircraft alignment

Upon touching down on the landing platform within  $\pm 3.9$ in, an ultrasonic sensor confirms the landing and wooden guides and a mechanical arm align the aircraft in yaw (Z-axis) (Fig. 4). The components are initially in a “homing position.” Along the X Axis from the rear to front of the payload exchange station:

Motor sizing was determined based on torque requirements to push the aircraft on the landing platform. The force required to push the aircraft on the surface of the landing platform was calculated to be 5.52oz/in with additional friction of moving the complete axis of 15.36oz/in. Total torque required was 21 oz/in for the entire alignment movement thus the alignment NEMA23 motors operate well under torque requirements for this system. (1) NEMA 23 stepper motor

pushes the aircraft along the X Axis into position for flight battery removal. The axis consists of 1010 1" x 1" T-slotted extruded aluminum bolted to linear bearing carriage assemblies which move along 4-ft x 3" flat steel. The motor was sized appropriately (125 oz-in torque) to push the weight of the aircraft on the X-axis toward the front of the platform on a low friction surface. The motor is connected to a belt drive with aluminum timing belt gears and 5m x 10mm, 6.5 mm bore belts. To align the aircraft consistently after each landing, appropriately shaped medium density fiberboard helped orient the aircraft about the Z-axis. The shape causes the Z-axis to slowly push and rotate and the aircraft to its final position and orientation. Once the alignment is complete and confirmed, A NEMA17 (63.7 oz-in) stepper motor with belt drive begins moving a 3D printed leg grabber along the Y-axis.

(2) A landing-leg capturing apparatus accepts the aircraft's vertically oriented landing legs (10mm carbon-fiber rods). In one motion, the jig captures and secures both of the front legs so it is ready for the battery exchange process.

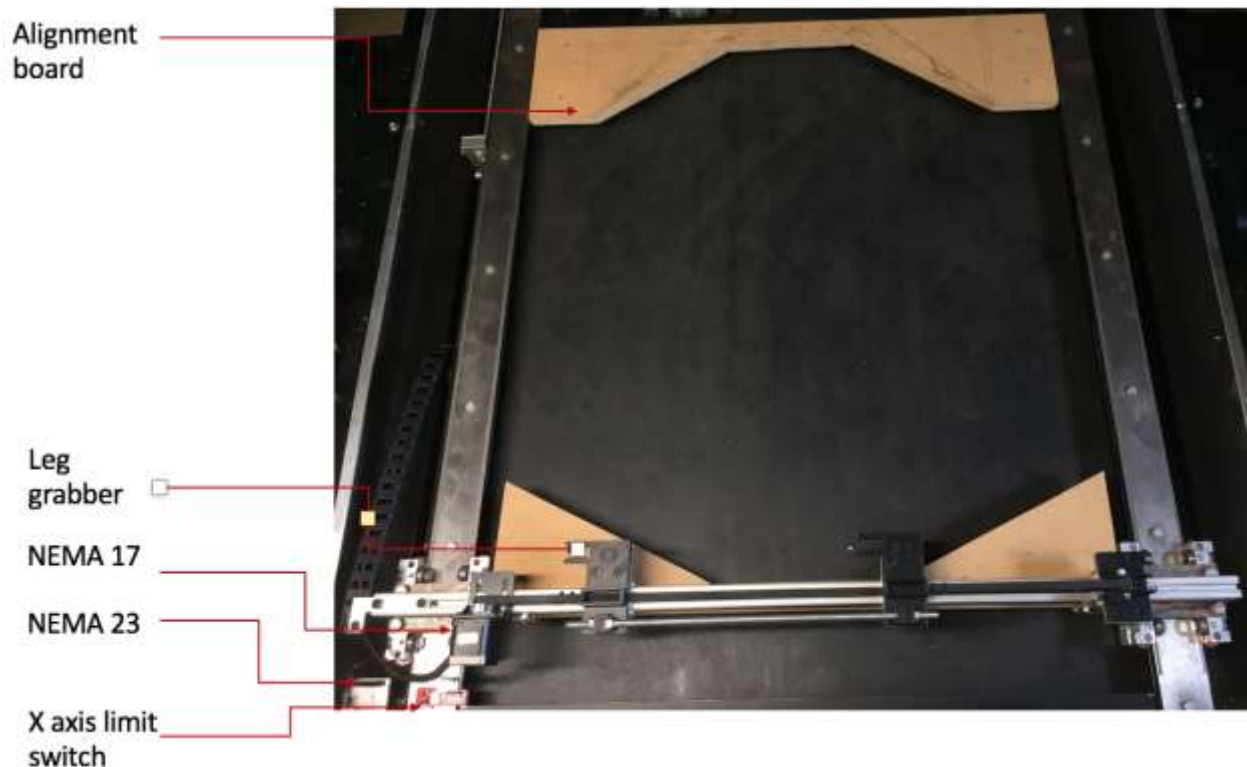


Figure 4: Aligning and securing the aircraft.

## 2.4 Battery Exchange



Figure 5: Battery exchange mechanism.

Each axis moves by a high-torque (420 oz-in) low inductance NEMA23 stepper motor with a Leadshine 3-Axis MX3660 motor driver (Fig. 5). The X-axis is guided by a 72 in x 3 in x ¼ in flat-rolled steel bar, and the Y-axis and the Z-axis are guided by pairs of 55” 20mm diameter case-hardened steel rods. At the base of the X axis, extended aluminum linear carriages provide sufficient torsional rigidity. Each Linear carriage is outfitted with 4 ABEC7 bearings which have a high moment load rating. The drive system moves slowly to prevent backlash and inaccurate battery placement. To ensure accurate battery exchanges, the X-, Y-, and Z-axes use 39” lead screws with ½-10 thread forms that travel ½” per rotation. The enclosed 16000mAh batteries move along the Z-axis from the storage bay up to the multirotor drone.

## 2.5 Control hardware

The control hardware consists of two stacked Arduino Mega boards based on the Atmega2560 microcontroller, each powered by 5V (Fig. 6). The top board controls the alignment system with a RAMPS CNC shield motor controller and the bottom board (underneath) controls the Leadshine MX3300 3-axis motor controller. Script created in the Arduino IDE environment interfaces with the ultrasonic range detector, limit switches, and stepper motors to control the exchange sequence, described in section E.

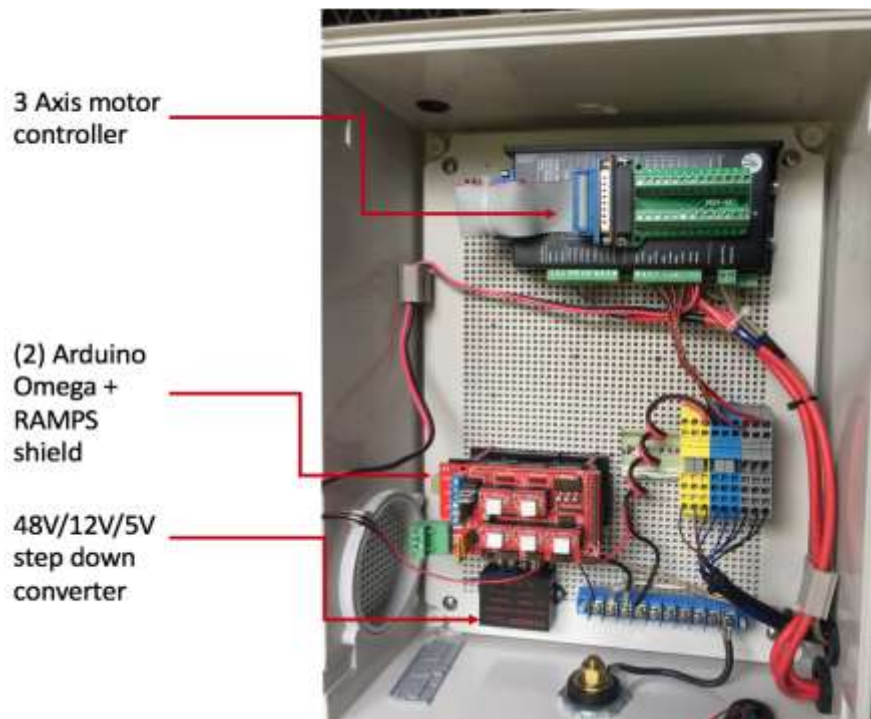


Figure 6: Electrical box.

## 2.6 Exchange sequence

Successful battery exchange is accomplished by first tuning each axis stepper motor to ensure precise movement in the battery exchange sequence. Steps in each sequence of the payload exchange have been recorded for timing and power usage statistics.

The x axis has 1.8 degree step angles and completes one revolution in 200 steps at a linear distance of 12.7mm. Therefore, at total length of 1524mm the motors translate the distance of the x axis in 30.48s. The y and z axis motors translate their respective distance in 36.56s. The aircraft movement to back position for takeoff required 24.48s reaching a total battery exchange sequence time of 91.52s.

The battery exchange sequence is as follows:

1. Confirmation was received at the ground station from the ultrasonic sensor that the aircraft has landed on the platform.
2. The X-axis and Y-axis stepper motors move to their homing positions. The alignment sequence begins. The X-axis pusher begins moving the aircraft into position.
3. When the aircraft is ready to be secured (after a certain number of X-axis steps), the Y-axis stepper motor moves the leg grabbers until they lock around the front two legs of the aircraft and sends a signal to the bottom board to begin the battery exchange.
4. The bottom board performs the movements of the three axes to retrieve the battery from the aircraft.
5. Once retrieved, the 3-axis battery exchange mechanism moves the empty battery to the charging bay and loads for recharging.
6. The battery exchange mechanism moves to the next fully charged battery and retrieves it.
7. The battery exchange mechanism inserts the fully charged battery into the aircraft.
8. The bottom board commands the top board to push the aircraft toward the center of the landing platform, release the leg grabber from the aircraft, and initiate its launch sequence.

Note, before the exchange sequences, waypoints were already uploaded onto the aircraft for its autonomous mapping mission. The aircraft lands on the platform, either after finishing its mission or after it reaches its low battery threshold. When reaching its RTL point it begins its descent to

the platform. Using RTK GPS, the flight controller guides the aircraft to the exchange station platform, landing the aircraft on the platform within its 3.9 in tolerance.

The system can be used with different levels of autonomy that expand the capabilities of a traditional unmanned aircraft survey. The system can employ autonomous operation based on command information that one enters on-site. Further autonomy can be achieved with the ability to update command information remotely using a 4G network. In particular, Mission flight planning and control of the aircraft can be created in Ardupilot Mission Planner software and then run through a remote desktop connection with a given IP address. This includes flight path generation, distance between runs, obstacle avoidance, assignment of altitude, return to home points, wind corrections, camera parameters, etc. In the event of an anomaly such as a failed landing or landing with too large an angle on the yaw (z) axis, the station will remain or return to home position. During flight, should command/control link or telemetry signal be lost, the aircraft will return to launch point and reconnect within sufficient range to the transmitter.

## 2.7 Monetization

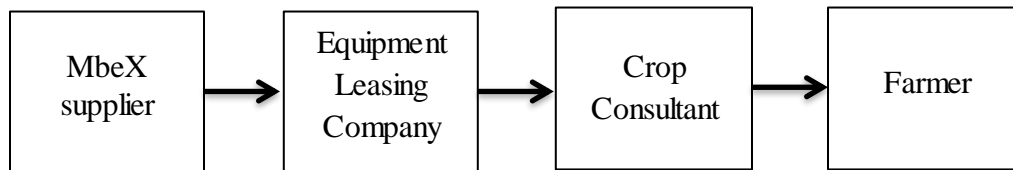


Figure 7: Supply chain.

A plausible monetization scenario with this supply chain is described below. The *MbeX* is referred to as the product.

**Product supplier:** First, it is assumed that the supplier makes an initial investment  $I$  given by  $I = I_F + I_P$  in which  $I_F$  is the investment made to acquire a feasible product (proof-of-concept phase) and  $I_P$  is the investment made in a prototype product (prototyping phase). Upon completing the prototype phase, it is assumed that the supplier receives orders for products. Assuming a product unit cost of  $C_M$  and a sales price of  $2C_M$ , the unit profit of  $U_M = 2C_M - C_M = C_M$ . The number of

products ordered for breakeven is  $M_B = I/C_M$ . The supplier becomes profitable when the number of orders  $M$  is greater than  $M_B$ .

**Equipment Leasing Company:** Assume that the equipment leasing company purchases  $M$  products from the supplier, leases  $L$  products from crop consultants over one season (year) at a unit leasing cost of  $U_L$ . The leasing company's payback period in years is  $P_L = (MU_M)/(LU_L)$ . If the leasing company purchases the same number of products as it leases in one year, then the payback period is  $P_L = U_M/U_L$ .

**Crop Consultant:** Assume that the crop consultant serves  $N_F$  clients (farmers) that lease one product each, that each client has  $N$  fields and that each field is scouted  $N_S$  times each season. The time (in days) for walking scouting  $N$  fields is  $T_W$ , the time in days for aerial scouting  $N$  fields is  $T_A$  and the walking reduction measure is  $\alpha$ . The total time to cover  $N$  fields when using the product is  $T_M = T_A + \alpha T_W$ . Assuming that an agricultural technician is paid  $D$  US\$/day (8 hours), The walking-only profit over one season and the differential profit over one season that arises as a result of using the product over not using the product are  $P_W = DT_W N_F N_S$  and  $P_D = D(T_W - T_M) N_F N_S$ .

## Results

According to multiple crop consultants in separate regions of North Carolina, there are several consistent principles used in determining the overall trade-off for fields which yield sufficient revenue margins. Of the total amount of fields scouted, 54% of those fields are within 20 miles to the business headquarters while the remaining fields are within 60 miles of the headquarters. Actual field sizes are 10-15 acres which are scouted individually in 80-100 acre plots in a zig-zag pattern. In one hour, one person can scout a 10-15 acre field. Traditional UAS survey requires 10 minute setup/breakdown time, with an additional 40 minutes flight time for 100 acre plots.

In February 2017, Land O' Lakes, Inc. drew international competitors in a crowd sourcing 'Drone Challenge' competition to help validate end user-friendly drone solutions helping farmers



make better crop management decisions thereby increasing operation efficiency and producing more valued crops. It's no surprise that agriculture technology experts are experimenting with the use of drone technology to help analyze data from large area surveys. In Watkins, Minnesota airborne drones were used to gather data from a 5,000 acre row crop operation. Over 157 innovators were gathered from 47 countries to help guide and encourage the use of unmanned vehicles in this challenge.

### 3.1 Performance

In this section, walk-only scouting with two-step scouting with and without MbeX stations are compared. Throughout the comparison, the following variables were considered. Pertaining to walking, it is assumed that a scout can walk 15 to 80 acres in one hour, represented by the variable  $A$ . We also estimate that the scout works 4 to 12 hours in a day. Field sizes up to 750 acres are considered, represented by the variable  $S$ . Pertaining to travel time, one can distinguish between using local crop consultants and those who must drive in from long distance or fly in for the scouting. It is assumed that the local crop consultants are not paid for their travel to and from the field but are paid for the travel between fields (during which they are on the clock). It is also assumed that the employment of an MbeX station eliminates travel time to and from work (which the employer does not cover) and the labor costs of the drone scouting. Pertaining to the walking reduction measure, denoted by  $\Omega$  (whether with or without MbeX stations), a range of 10% to 25% is assumed. In other words, flying the field results in the need to walk 10% to 25% of the field. Finally, in terms of revenue, an assumption is made that a crop consultant charges 5\$ per acre. As a baseline, that crop consultant receives a zero profit from walk-only scouting. Thus, the profits shown below come from two-step scouting relative to walk-only scouting.

The number of days required to complete the walking of  $N$  fields and the flying of  $N$  fields was determined by the methodology described in the method section. The comparisons begin with two performance plots: first plots of number of days to walk a field versus field size for different numbers of fields, as shown in Fig. 9, and, secondly, plots of number of days to fly a field versus field size for different numbers of fields, as shown in Fig. 10.

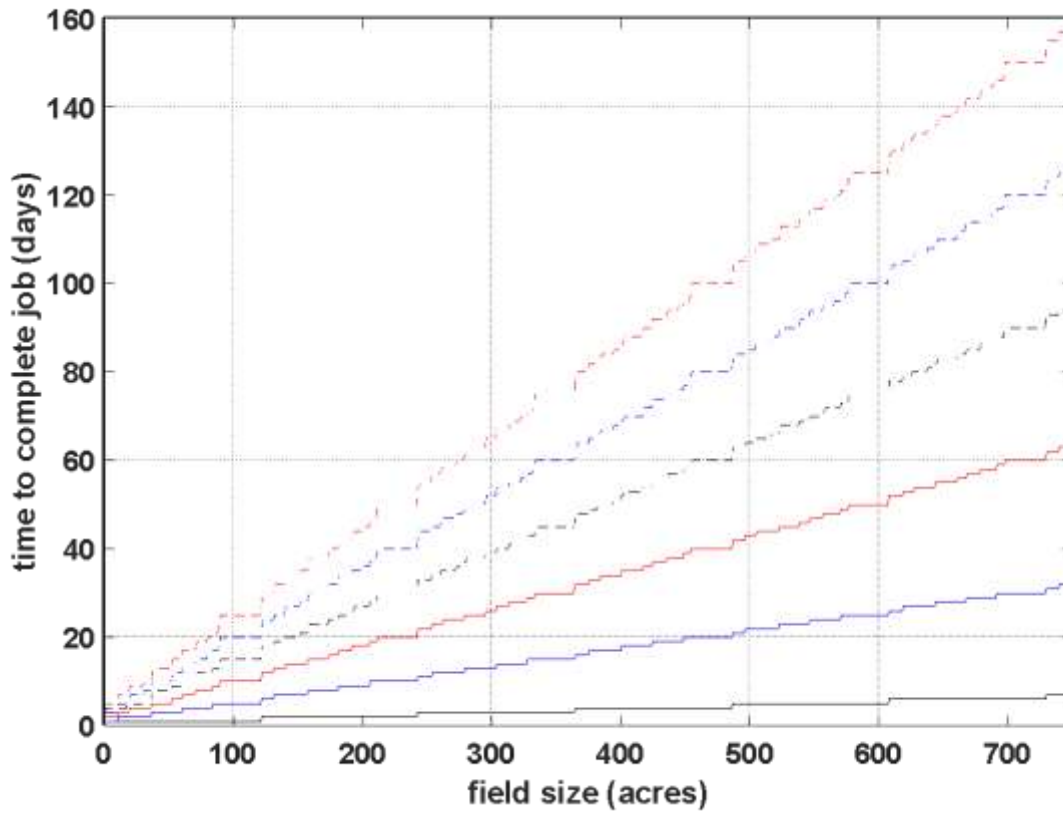


Figure 9: Time to Walk  $N$  Fields ( $N = 1, 5, 10, 15, 20,$  and  $25, A_w = 15, T_{travel} = 1$ ).

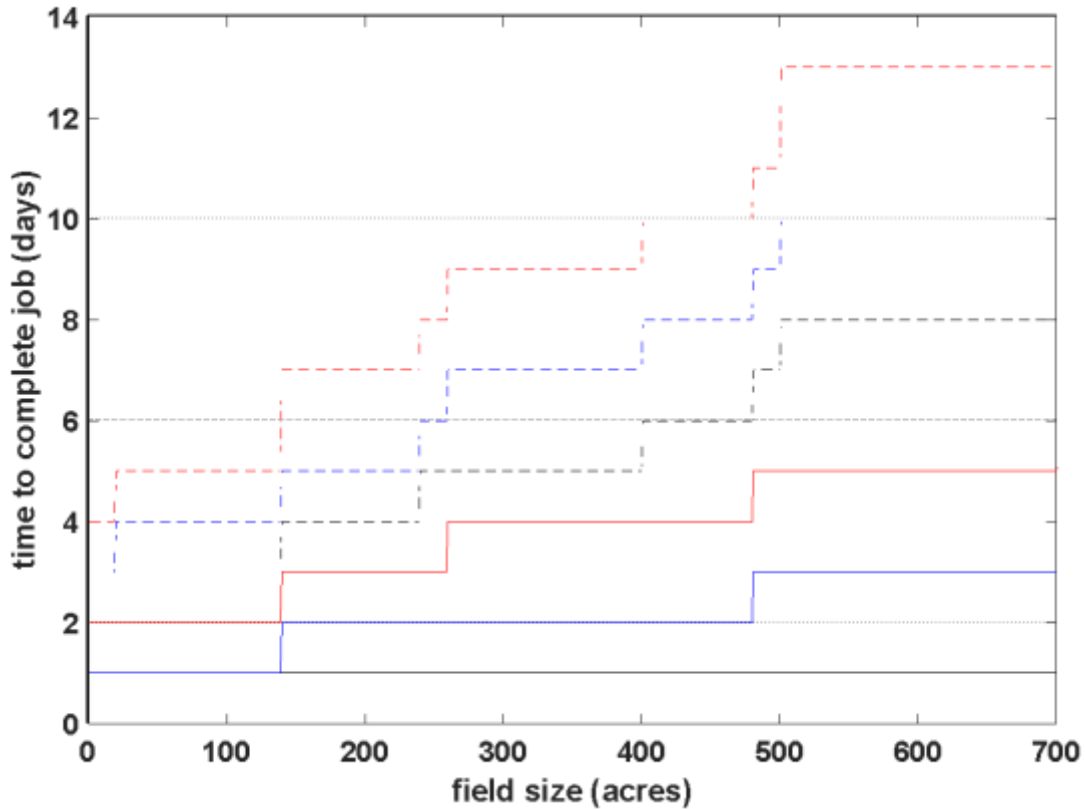


Figure 10: Time to Fly  $N$  Fields versus Field Size ( $N = 1, 5, 10, 15, 20, 25, A_F = 200, T_{travel} = 1$ ).

For the purposes of comparison, we assumed that the crop consultant walks a field in  $A_W = 15$  acres per hour and flies a field in  $A_F = 360$  acres per hour. However, we assumed a travel time of 1 hour between fields and therefore that the crop consultant would end a day if there was less than 2 hours left in a day when completing a field (instead of continuing on to the next field that same day).

The calculations needed to compare walking with two-step scouting are based on these two plots. For example, say that a crop consultant is tasked with assessing  $N = 10$  fields, each  $S = 500$  acres. From Fig. 7, it requires 43 days to walk all of the fields (without flying). Say that the walking reduction measure is  $\Omega = 10\%$ . Employing the two-stage scouting, the field size that needs to be walked is  $S = 500 \Omega = 50$  acres. From Fig. 8, it requires 2 day to fly all of the fields and from Fig. 7 another 6 days to walk all of the fields. We also assume that data processing requires  $A_P = 60$  acres/hour which requires an additional  $SN/A_P = 500(10)/(60 \cdot 8) = 10.42$  days. The walk-only

scenario of 43 days reduces to the two-stage scenario of 18.42 days (without MbeX stations) – a savings of a factor of about 2.3. If MbeX stations are employed, the 18.42 day scenario reduces to a 16.42 day scenario of paid labor – an additional savings of 11%. This is just one example; the savings depend largely on the sizes of the fields, the travel time between fields, whether or not the crop consultants are local, and the image processing time.

### 3.3 Failure/Reparability

The section describes the MbeX system toward gaining an appreciation of the future levels of reliability in these kinds of systems. It is expected that these systems will require some level of maintenance pertaining to customized parts; failure will most likely occur in the electrical connections and mechanical joints. Preventative maintenance would follow a checklist of repair procedures for electrical connectors, solder joints, ESC replacement, and motor/bearing replacement. The measure of expected failure and reparability can be deduced from assessing the system's complexity (See Table 2). It is not anticipated that all of the repairs can be performed, or would be better formed, on-site, and therefore the system is mobile.

Table 3. MbeX Complexity

Section	MbeX	Cost	% Fabrication	Troubleshooting	Reparability	Total Time	Connections	Electrical
Trailer/ Substructure		\$1,260.52	50	2	2	4	0	
AC Power		\$174.16	0	2	2	4	15	
DC Power		\$238.21	0	9	9	18	22	
Linear Motion Mechanical		\$1,139.82	18	16	19	35	209	
Linear Motion Electrical		\$1,192.82	0	33	26	59	54	
Quadrotor Drone		\$846.18	11	19	16	35	132	
Flight Battery System		\$2,561.08	27	10	11	21	44	
Miscellaneous		\$8,797.78						
Totals		\$16,210					476	

As shown in Table 3, the MbeX system is divided into 8 subsystems, each showing their cost and the percentage of those parts by part count that are custom fabricated as opposed to being off-the-shelf. The custom parts tend to be less reliable than the off-the-shelf parts. Also shown for each subsystem, is the average time to trouble shoot a failure, repair the failure and the total of the two. Finally, for each subsystem, the number of connections is given, again, these tend to represent points of potential failure. The following characterizes the level of failure and reparability of the MbeX:

- Assuming that connections fail more than COTS parts (parts are manufactured and connections are made manually), and since we have 292 COTs parts, of which 52 are breakable, and 5556 connections, of which X are breakable, it follows that the failures are dominated by the connections.
- Average number of parts in a section is 35.5. The most is the trailer/substructure and the least is DC power.
- There are 8 sections, average section cost is \$1099.72. The smallest section cost is AC power (\$174.16) and the largest is the Flight Battery System (\$2,561.08).
- Average COTS part cost is \$25.39. The largest parts costs are the trailer (530\$), etc.)
- A total of 91 hours to identify the failure of 52 parts for an average of 1.72 hours per part. And another 85 hours to repair the part for an average of 1.63 hours per part, for a total of 3.35 hours per part. At a cost of 50\$/hour, the average cost to identify and repair a part is \$167.50. The largest is X.
- The two subsystems that have the most connections are the mechanical linear motion parts at 209 and the quadrotor drone parts at 132. The mechanical linear motion parts are 18% fabricated and the quadrotor drone parts are 11% fabricated but the quadrotor drone connections are less reliable than the mechanical linear motion parts because the latter experience much greater hours of service.

### 3.4 Digital farm feasibility

The proof-of-concept *MbeX* described in the previous sub-section exhibited levels of failure and repair that fall in line with best practices. Moving ahead, the data provided in the previous sections provide a means of assessing scenarios that could practically lead to digital farm feasibility wherein the justification is based on a cost savings without the need to justify feasibility on the basis of improved crop performance. The total hours required to develop the proof-of-concept was 1500 hours (See Table 4).

Table 4: Hours spent to develop the proof-of-concept *MbeX*.

<b>Subsection</b>	<b>Work performed</b>	<b>Total Hours</b>
<b>Trailer/substructure</b>	Design (1); Rapid Prototype (4); Assembly (2); Testing (1)	12 hours total
<b>Linear motion control hardware</b>	Perf boards, Motor controllers, Breakout (GPIO), switches, wire stepper motors and limit switches	16 hours total
<b>Linear motion electrical</b>	Design (2); CNC runtime (4); Assembly (4); Test and evaluation (1)	11 hours total
<b>Software development requirements</b>	Raspberry pi with Python driven application; Voltage sensors integrated with Raspberry Pi to detect individual battery voltage; Ideation (8); Hardware Fabrication (32); Software Design (40); Software Development (40); Software Testing for prototype (8)	128 hours total

Monetizing this, the estimated investment by the supplier for the proof-of-concept is estimated at  $I_P = (1500 \text{ hours})(100 \text{ \$/hour}) = \$150\text{K}$ . Prototype development is estimated to be twice that at  $\$300\text{K}$  so the total initial investment is estimated at  $I = \$450\text{K}$ . Assume that the supplier serves an area in which the crop consultants average  $N_F = 40$  clients that each orders one

product and that the supplier has signed up 10 crop consultants. The total number of initial orders is then  $M = 400$ . The cost of the unit product is composed of a parts cost of about \$16,000 per Table 3 and a labor assembly cost that was estimated at  $(25 \text{ hours})(\$100/\text{hour}) = \$2500$  for a total cost of \$18,250. Adding an overhead rate of 100%, the total unit profit is  $C_M = \$18,250$ . The breakeven number of orders is  $M_B = I/C_M = \$450K/\$18.25K = 24.7$  units. The initial order of 400 units well exceeds the breakeven number in the first season.

Next, consider the leasing company. The sales price of a unit product to the leasing company is \$36,500. Assume that the leasing company set a leasing charges per season of  $U_L = \$5000$ . The leasing company's payback period is then  $P_L = U_M/U_L = \$36.5K/\$5K = 7.3$  years.

Next, assume that the crop consultant's clients average  $N = 5$  fields, each of a size of  $S = 100$  acres and that the walking reduction measure is  $\Omega = 0.1$ . From Figures 9 and 10, it requires  $T_W = 4$  days to walk the fields and  $T_A = 1$  day to fly the fields and thus  $T_M = 1 + 0.1(4) = 1.4$  days to walk and fly the fields. Assuming that an agricultural technician is paid  $D = 15\$/\text{hour}$ , the differential profit is  $P_D = D(T_W - T_M)N_F N_S = (15\$/\text{hour})(3.6 \text{ days}/\text{inspection})(8 \text{ hours}/\text{day})(5 \text{ fields}/\text{client})(40 \text{ clients})(16 \text{ inspections}/\text{season}) = \$138,240$ . The crop consultant's leasing cost is  $(40)(5000) = \$200,000$ .

## Summary and Conclusions

This thesis recognized that visual acuity naturally divides into that which is tasked with identifying whether or not a plant is healthy and, if not, diagnosing the problem, and recognized that this distinction can be the basis of dividing up scouting into drone scouting and aerial scouting. Moreover, the thesis recognized that this leads to an exciting opportunity for the practical use of drones in agriculture. Toward further pursuing this line of reasoning, the thesis considered two methods for course-scouting. We first compared aerial & walking scouting with walking scouting and then compared MbeX aerial scouting & walking scouting with aerial & walking scouting (without MbeX). The thesis then examined the complexity of the MbeX by designing and fabricating an MbeX, which was described in detail in the method section. The key questions were 1) whether and to what degree two-stage scouting is more efficient than walking scouting, and 2)



whether and to what degree the operator-free UAV is more efficient than the on-site operated UAV. Toward answering these questions, the thesis first developed an algorithm that determines the number of days required to complete the scouting of  $N$  fields, recognizing that this applies to both UAVs and walking. The thesis then developed a walking reduction measure, recognizing that the savings from drone use ties strongly to the percentage of the field that has potential problems, which depends on the application. The data shows that two-stage scouting is significantly more efficient than walking scouting. As explained, in a representative scenario given in the results section, the two-stage scouting could be performed with less labor by 230%, which is tremendously significant. The data also shows that the MbeX provided an additional savings of 11%, which is significant, too. It became even greater when the travel time to and between fields grew significantly. Pertaining to the MbeX system, the prototype and software cost about 16,000\$ and the two subsystems that had the most connections, driving repair needs, were the mechanical linear motion parts and the quadrotor drone parts.

Overall, two-stage scouting offers wide-ranging opportunities to both small and large scale agriculture. The opportunities are immediate, *not* requiring as of yet developed technologies, enables data acquisition that is much more rapid, and at a cost that is on the order of half that which is currently in practice. In the future, systems such as the MbeX, will be able to offer even greater opportunities. With MbeX, data access becomes on-demand, labor costs for scouting become marginalized, and it can serve as a gateway that enables a lot of the applications for crop health that are under development to be implemented.

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## **APPENDICES**

## Power

All of the equipment on battery exchange station runs on DC power. Low power consumption was a key factor in the design. Assume a \$0.10/kWh energy cost and that each flight battery has a capacity of 16Ah at nominal 22.4V for a total capacity of 358.4Wh. Out of 358.4Wh, only 80% can be used, that is, 284.16Wh. Two chargers charge five flight batteries (four in the battery box and one on the aircraft) over 12 hours at 16Ah consuming 6,819.92Wh for an average cost of \$.68 (See Fig. 7). For applications where AC 120V power is available on site, there are several AC-DC power supplies located on the trailer underneath the landing platform. Two 12VDC 50amp, 600W power supplies provides current to the flight battery charging system which charges at a maximum of 96amps DC. Power is provided to the alignment system by 1 12VDC 30amp, 360W power supply. One 48V, 7.8amp power supply powers the Leadshine MX3660 stepper motor driver which powers the 3 motors for the battery exchange. Power is also regulated to 5V with a step-down ‘buck’ converter to power the two boards.

The battery exchange system was required to operate remotely for 24 hours on its own source power. To accomplish this, the system was outfitted with 8 12V 100Ah absorbed glass mat lead acid batteries. While most of the consumption of power goes to charging the batteries, savings can be gained by efficiently operating the battery exchange. To maximize efficiency, a 48V DC power requirement for the battery exchange was implemented. The higher voltage (and lower current) extended the endurance of the operation. When operating on reserve power alone, the exchange station had a budget of 7.2kWh. Over 12 hours of continuous flight battery charging, the system consumed 6880.40Wh. Each 90 second exchange sequence required a total of 241.92Wh. The entire system therefore requires 7122.32Wh for 12 hours of full capability operation. This equates to 593.53Wh per hour at full operational capacity allowing 28 flights over 12 hours, or 1 flight every 26 minutes.

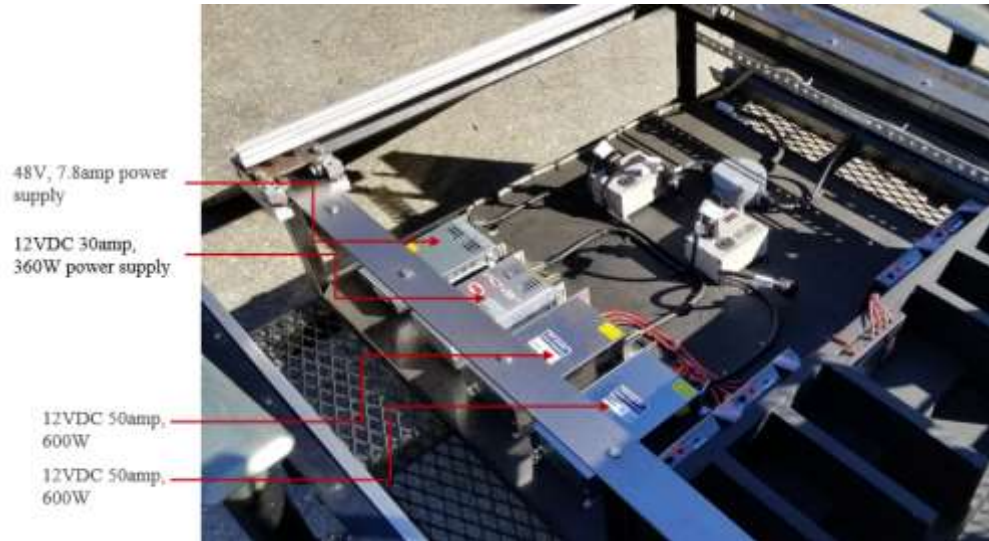


Figure 8: Power Supply.

In remote location operation over an extended period, a generator can provide 10 hours of power of full capability operation. Outfitted with this equipment, the exchange station is capable of 23 flight battery exchanges during the generator operation.

In a crop survey scenario, 7 flights could operate from 11AM to 1PM during the best imaging hours of the day. In this scenario, the battery exchange system could operate remotely over a 7-day deployment with sufficient power reserves.



Figure 11: Battery Enclosures.

## Requirements

The multicopter aircraft was designed with capabilities of the battery charging system in mind. While the system is capable of charging each flight battery at 48amps, the battery manufacturer recommended charging rate is 16amps to ensure longevity of the flight batteries (Fig. 8). Thus, one flight battery will be charged to full capacity every 26 minutes, this becoming the required flight endurance. Two platforms were designed for this system both which have identical physical frame dimensions of 650mm/25.59in diagonally. The second aircraft has coaxial motors configured on each arm of the frame bringing the total number of motors to 8. The first platform (X8) achieved a 26 minute mixed flight time and 42.8 minute hover flight time. The second platform (X4), with only 4 motors, achieved a mixed flight time of 20.0 minutes with a hover flight time of 25.4 minutes (Table 1). While the 8 motor platform did perform with higher efficiency and greater flight times, the physical constraints of the battery and camera payload determined the decision to use a 4 motor platform.



Table 2: Flight Performance.

<i>Data</i>	<b>X8</b>	<b>X4</b>
Hover Flight Time(min)	42.8	25.4
Mixed Flight Time(min)	26	20.0
Weight(g)	3922	3731
Thrust to Weight(g/W)	4.0:1	2.1/1
Max Speed(mph)	17.4	21.1

The aircraft frame uses a Toray 3K cloth woven carbon fiber board with 3K hollow twill pure carbon fiber tube for light weight and rigidity and is 600mm diagonally from center to center of the out-runner motors. The motors are 4008 Martin Hale long endurance 24pole, 330kv brushless motors. These motors provide a 2.1:1 power to weight ratio which allows sufficient maneuverability in adverse autonomous flight conditions. Oversized bearings offer longer maintenance intervals and less fatigue when compared to other motors. Integrated strobe lights are required for night time operation and can be outfitted on the frame if the mission requires. Electronic speed controllers (ESC) are 40 amp units (Hobbywing Xrotor Pro series) with LED navigation lights built in. Oversized for this application they allow for lower temperature operation under load, a key attribute in reliability. The number one failure we have seen in multi-rotors is in the ESC components and special consideration has been given to this in the design.

Since power flow and voltage drop-off was one of the factors that led to past testing failures, all wiring was completed with 14 guage awg wire. The flight controller is a developer friendly Pixhawk 2.1 Cube Controller. It offers a triple redundant IMU with dual redundant power supplies making this a highly reliable autopilot. The carrier board has an Intel companion computer for in-flight processing. A heated IMU extends its cold weather capabilities and its Mission Planner software has parameters necessary for custom solutions. Command and control is accomplished over 1.2 GHz frequency and offers emergency manual operator control during testing, or in

emergency control. Multiple fail safes are built into the Pixhawk firmware, any one of which will trigger a return to home signal sent over Mavlink. Using RFD900 telemetry units we have boosted the Mavlink signal strength to 1000mW increasing signal strength over 10 times the standard unit. Signal ranges of greater than 15 Km are now possible.

## Flight Test Experiment Design

Flights were conducted in a field size suitable for separate flyovers of areas. Prior to conducting the flight experiments, wind speed/direction and temperature were recorded to help understand environment and vehicle performance. Additional criteria for the selection of field for mapping include minimal elevation changes, obstacle clearance in landing/takeoff zone, area of uncontrolled airspace, and adherence to checklist protocol during all operations. Images were captured during preprogrammed flights. Post processing served to reveal Total capacity (mAh) consumed, total flight time, average ground sampling distance, total area coverage, and time for initial post processing.

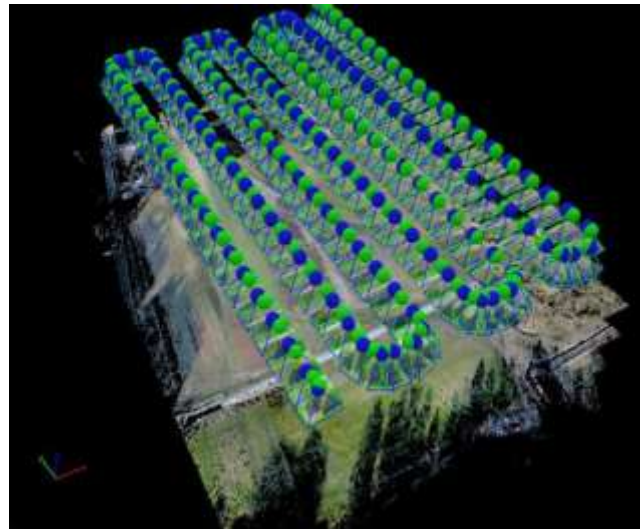
## Flight #1 - 10/18/18

### Mission Notes:

62 degrees farenheit, partly cloudy, winds variable 3-5 mph  
SEP3 Battery (5350mAh)  
Takeoff - 3:38 pm 91% battery capacity  
Land - 3:48 pm 54% battery capacity, 15.39V

### Mission Parameters:

AGL: 397ft  
Area: 25.13 Acres  
Max horizontal waypoint navigation speed: 40.0ft/s  
Adaptive Bank and Turn enabled  
1.3 inch GSD  
75% forward overlap  
75% side overlap  
AGL Tolerance: 9.84ft



**Total mAh consumed: 1,980 mAh**  
**Total Flight Time: 10 minutes**  
**Average Ground Sampling Distance (GSD): 1.24in**  
**Area Covered: 62.45 acres**  
**Time for Initial Processing (without report): 2hrs 50mins**

Fig. 12: Flight #1 Waypoint camera trigger and cameras showing GSD

## Flight #2 - 10/18/18

### Mission Parameters:

AGL: 1499.5ft

Area: 25.13 Acres

Max horizontal waypoint navigation  
speed: 40.0ft/s

Adaptive Bank and Turn enabled

4.91inch GSD

75% forward overlap

75% side overlap

AGL Tolerance: 9.84ft

### Mission Notes:

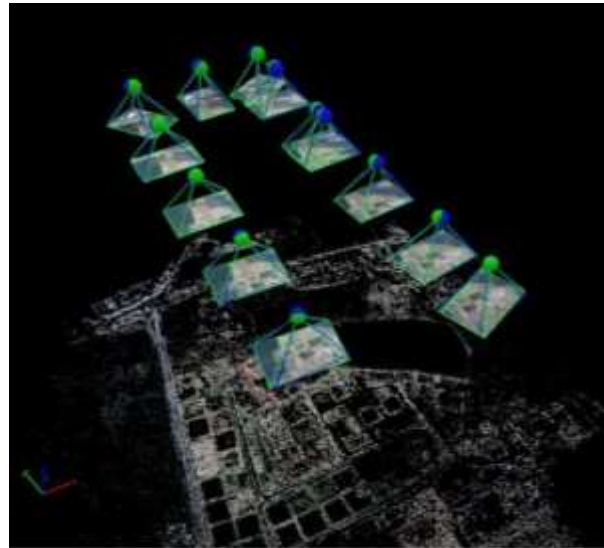
61 degrees fahrenheit, mostly cloudy,  
winds variable 3-4 mph

First attempt failed, waypoint #1 exceeded  
max distance to home location. Changed  
SEP2 to SEP1 battery. Possible increase  
in climb/decent speed to decrease total  
mission time.

SEP1 Battery (5870mAh)

Takeoff - 4:25pm 82%capacity, 16.35V.

Land - 4:33pm 54%capacity, 15.38V.



**Total mAh consumed: 1,644 mAh**

**Total Flight Time: 8 minutes**

### Post Processing

**Average Ground Sampling Distance(GSD): 4.74in**

**Area Covered: 125.066 acres**

**Time for Initial Processing(without report): 5mins 2 Seconds**

Fig. 13: Flight #2 Waypoint camera trigger and cameras showing GSD