The Applications of Autonomous Systems to Forestry Management

by

Joshua Przybylko

BE Aeronautical (Space), The University of Sydney, 2005
BSc Mathematics and Physics, The University of Sydney, 2005

Submitted to the MIT Sloan School of Management and the Engineering Systems Division in Partial Fulfillment of the Requirements for the Degrees of

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Signature of Author ______________________________
Engineering Systems Division, MIT Sloan School of Management
May 10, 2013

Certified by ______________________________
Steven D. Eppinger, Thesis Supervisor
Professor of Management Science and Innovation and Professor of Engineering Systems

Certified by ______________________________
Jonathan P. How, Thesis Supervisor
Professor of Aeronautics and Astronautics

Accepted by ______________________________
Oli de Weck, Chair, Engineering Systems Education Committee
Associate Professor of Aeronautics and Astronautics and Engineering Systems

Accepted by ______________________________
Maura Herson, Director of MIT Sloan MBA Program
MIT Sloan School of Management

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Abstract

Public and private timberland owners continually search for new, cost effective methods to monitor and nurture their timber stand investments. Common management tasks include monitoring tree growth and tree health, estimating timber value and preventing wildfire. Many of these tasks are both manual and costly due to the vast areas and remote locations involved.

Forestry experts predict that multi–vehicle autonomous systems may enable new, cost effective methods for performing various forest management tasks[1]. However, it remains unclear how these technologies may be applied, or where to focus development efforts. This research attempts to address this gap in literature, linking state–of–the–art research in forestry management science, robotics and autonomous systems, and product design and development.

This thesis begins by reviewing existing forestry management practices and discussing a number of challenges identified through industry interviews and research. Modern product design methods are reviewed, and used to generate ideas for a number of new concept systems. Three design concepts are presented as detailed case studies.

The data sets, methods and proposed systems discussed in this thesis may be used to guide future research in forestry management science, and drive further innovation in the emerging field of commercial and civilian autonomous systems.

Key words: *Forestry Management, Forestry Science, Robotics and Autonomous Systems, Unmanned Aerial Vehicles (UAV), Unmanned Aerial Systems (UAS), Product Design and Development, Light Detection and Ranging (LiDAR)*

Thesis Supervisor: Steven D. Eppinger
Title: Professor of Management Science and Innovation and Professor of Engineering Systems

Thesis Supervisor: Jonathan P. How
Title: Professor of Aeronautics and Astronautics

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1 Introduction and Motivation

1.1 Problem Statement and Research Objective

Over the past decade, significant progress has been made in the field of autonomous systems, including developments in sensor networks, unmanned aerial vehicles, unmanned ground vehicles and systems of unmanned vehicles, referred to as vehicle swarms[2]. Many of these advanced technologies are now used in the military[3]; however, applications in the civilian and commercial sectors are still in their infancy[4, 5]. As new regulations and protocols are established to enable the integration of unmanned aerial systems into national airspace, it is important to understand how these technologies may be applied across a variety of industries. A better understanding may help focus academic research efforts, inform policy makers and drive investment and innovation in the emerging field of commercial and civilian autonomous systems.

Forestry management is one such industry anticipated to benefit from the use of autonomous systems. A few early reports have attempted to discuss civilian applications [1, 6, 7] to forestry management; however, more research is required to understand the true potential. This thesis attempts to address this gap in literature by exploring the design process for autonomous systems with an emphasis on forestry management. The methods discussed in this thesis may be applied to additional industries as part of future research to provide a more comprehensive view of how society may benefit from autonomous systems.

This thesis begins by reviewing modern product design methods applicable to the design and development of advanced technologies. Forestry management practices are reviewed and a number of forestry challenges are presented based on findings from industry interviews. Three concept systems designed to address the aforementioned challenges are presented as case studies of the initial product design process. This thesis attempts to tie together the three interdisciplinary areas of research illustrated in Figure 1.

Research Contributions:

- Review of product design methods for the development of autonomous systems technologies.
- Review of current “state–of–the–art” technology and research in forestry science.
- Review of current “state–of–the–art” technology and research in the field of robotics and autonomous systems.
- Description of three new concept autonomous systems with applications in forestry management.
- Recommendation pertaining to future areas of investigation and research.

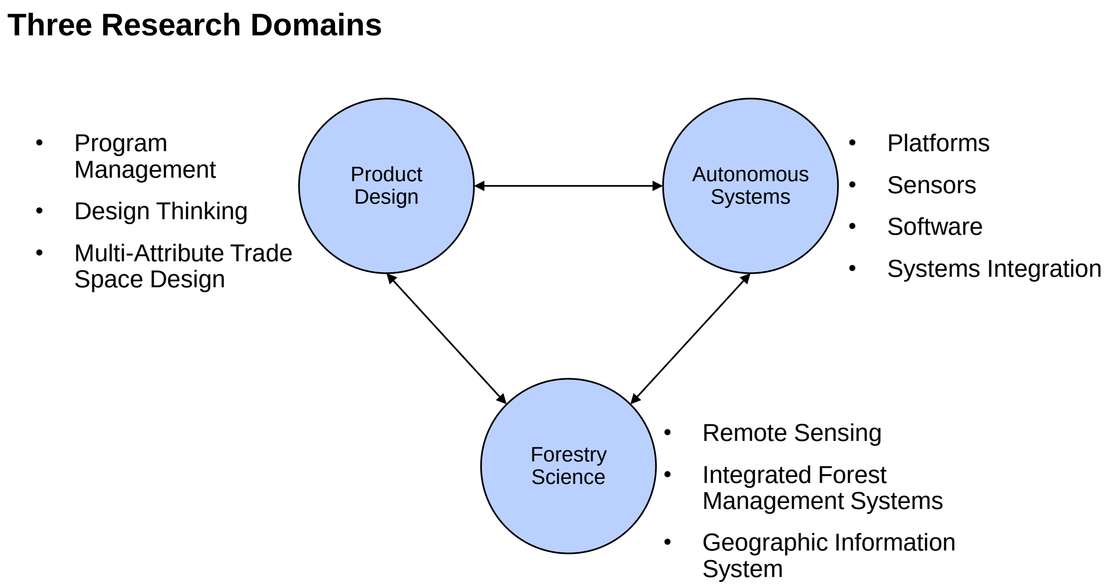


Figure 1 – Three Interdisciplinary Domains of This Research

1.2 Defining the Autonomous System

An autonomous system as described by this project may include multiple interacting platforms (agents), platform sub–systems, data systems, and human operators[8]. Such a ‘system–of–systems’ may be configured in a manner as to perform a number of functions to achieve an objective or mission. The system may include some level of autonomy or intelligence to more optimally achieve a mission goal. When an autonomous system involves more than one mobile platform, the system may be referred to as a swarming network of autonomous vehicles, or simply, a swarm. Figure 2 illustrates various elements that may comprise an autonomous system. A concept of operations may use various fixed and mobile assets, with varying degrees of automation and autonomy.

The primary advantages of autonomous systems is their ability to gather or process large amounts of information in relatively short periods of time to more optimally achieve a mission task, all while protecting humans from potentially hazardous or dangerous situations[9].

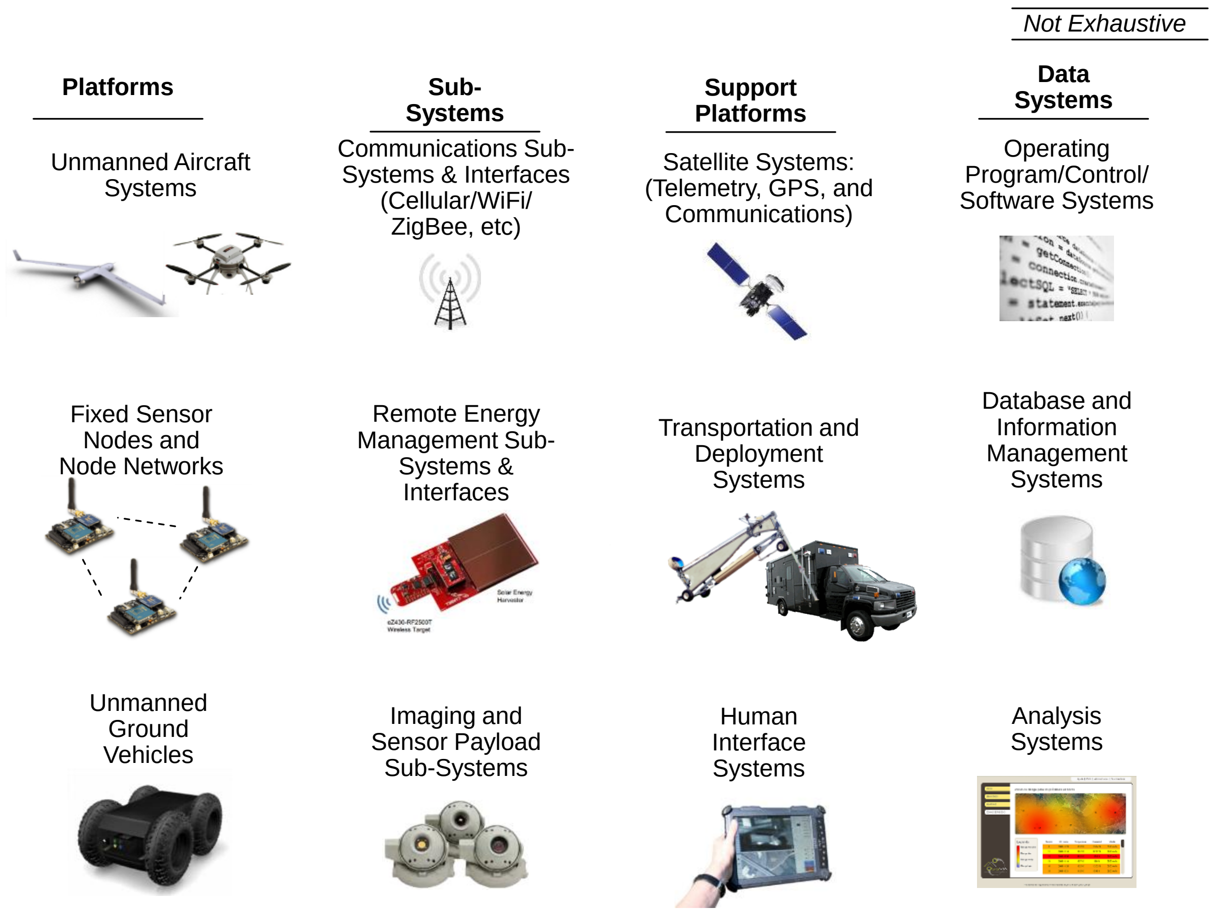


Figure 2 – Autonomous System Elements

1.3 Research Methodology

The research methodology largely followed the Opportunity Identification and Concept Development phases from the widely–adopted six–step product design process outline in the book 'Product Design and Development' by K.T.Ulrich and S.D.Eppinger[10]. The high–level process is outlined in brief in Chapter 2 of this thesis and in Figure 3. The process involved a combination of desktop research, industry interviews with forestry experts, interviews with experts in the field of autonomous systems and product design workshops.

1.4 Chapter Summary

One of the most challenging yet important tasks when developing any new innovation is the identification of a customer need that could be addressed with new methods, designs or technologies. We refer to these needs as market opportunities.

Chapter 2, therefore, begins with a review of popular idea creation and product design methodologies and how they can be adapted to guide the broad challenge of identifying new commercial and civilian applications for autonomous systems technologies.

Chapter 3 explains why forestry management was selected as the focus area for this research and sets the project charter and foundation for subsequent chapters.

Chapter 4 reviews the basic tasks involved in forestry management, an important step in the ideation process. Key market segments, active areas of industry research and technology trends are reviewed. Chapter 4 may be particularly useful to readers familiar with autonomous systems technologies but unfamiliar with the forestry management industry.

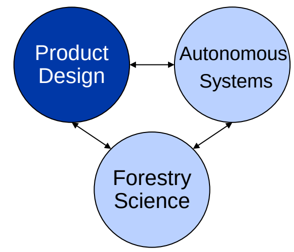
Chapter 5 reviews the structure of the civilian and commercial autonomous systems markets, areas of active development and technology trends. Chapter 5 may be particularly useful to the forestry researcher unfamiliar with autonomous system technologies.

Chapter 6 discusses a number of forestry management market opportunities, identified through industry interviews and workshops.

Chapter 7 explores the top three market opportunities in greater detail and describes three proposed concept systems, used as case studies for the product design methods outlined in Chapter 2.

Finally, Chapter 8 reviews the key learnings identified during this research and recommends further areas of investigation.

2 Product Design Methods for Autonomous Systems



A product development process is a sequence of steps or activities that an enterprise or team follows to conceive, design and commercialize a new product[10]. This research utilizes the first two steps of the widely adopted six–step design process outlined in the book 'Product Design and Development' by K.T.Ulrich and S.D.Eppinger[10]. Given the goal of this research is to explore new applications and ideas for autonomous systems and not to design a full prototype, only the first two steps of the six–step process are used in this work.

2.1 The Product Design Framework

In this chapter we review the important activities for the opportunity identification and concept development design phases outlined in Figure 3. For brevity, only the most important concepts are discussed and for a more in–depth discussion the reader is referred to the text 'Product Design and Development' [10].

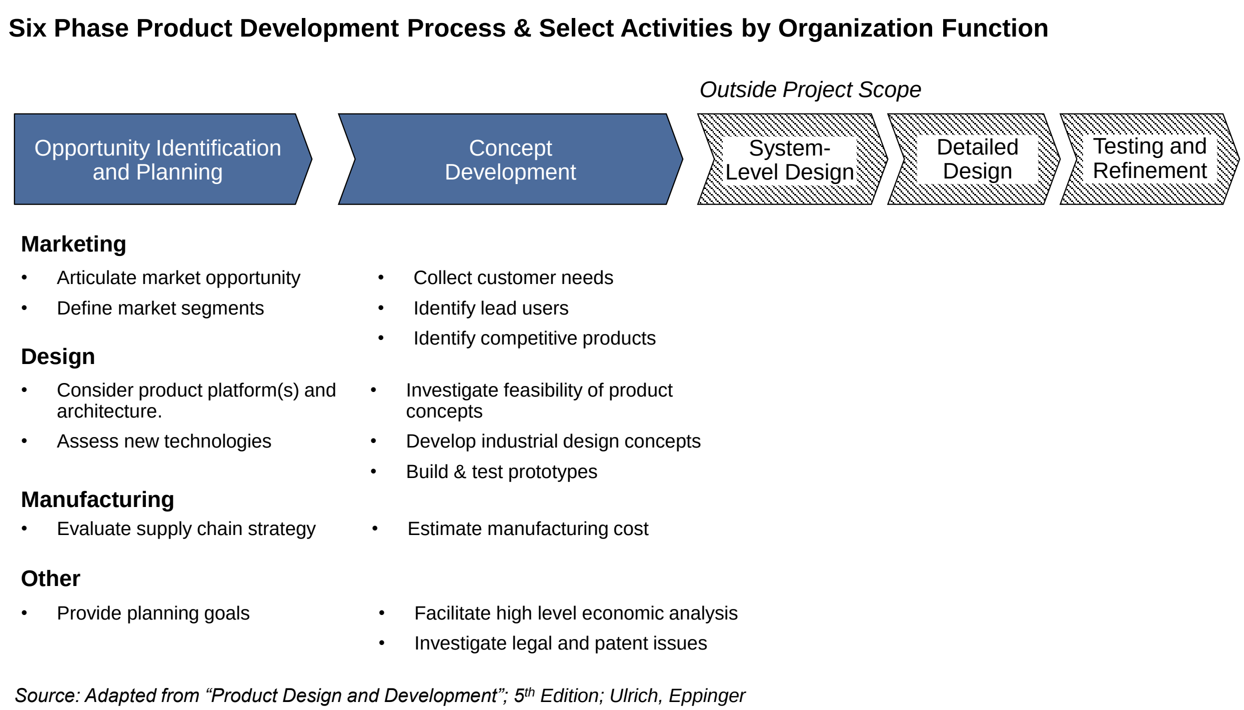


Figure 3 – Six Phase Product Development Process by K.T.Ulrich and S.D.Eppinger[10]

Other relevant design frameworks include the ten stage process of Figure 4, initially proposed in the text 'Unmanned Aircraft Systems: UAVS Design, Development and Deployment'[11]. Another comprehensive design methodology for unmanned aerial systems can be found in the text 'Designing

Unmanned Aircraft Systems – A Comprehensive Approach'[12]. Both approaches in the aforementioned texts, however, are more specialized towards multi-million dollar Unmanned Aerial System projects, with emphasis on military applications. Therefore, the more generic process by K.T. Ulrich and S.D. Eppinger[10] was deemed more relevant to the task of designing commercial and civilian autonomous systems.

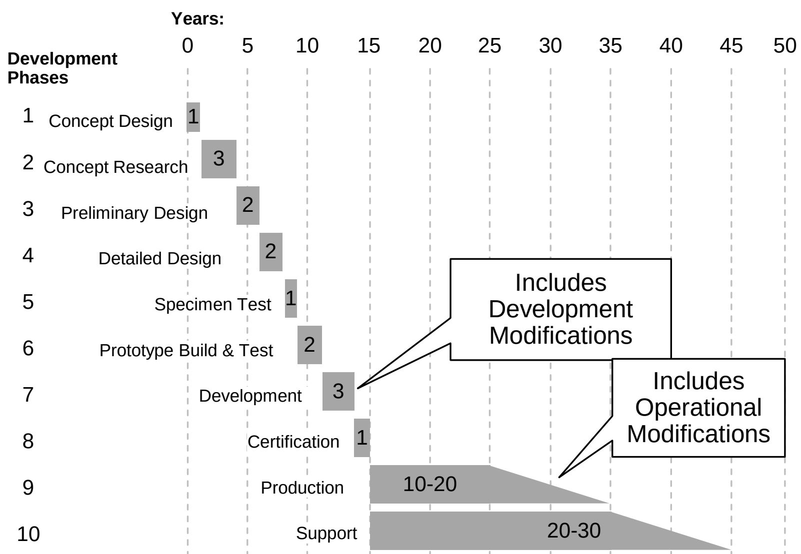


Figure 4 – Phases of UAS development by R. Austin[11]

Opportunity Identification and Planning

The objective of the opportunity identification and planning phase was to narrow the scope of the project to a particular industry, segment and market challenge. This involved building a 'fact base' to help identify market challenge 'opportunities' and understand existing products and solutions. For example, during the planning phase a market assessment of the forestry industry was conducted (Chapter 3 and 4), as was a review of the autonomous systems market (Chapter 5).

As described in the book 'Product Design and Development' [10], the planning and opportunity identification phase can be further broken into the following six steps. Each step may be mapped to a particular chapter of this thesis. A detailed explanation of each step may be found in the text.

- **Establish a charter** **[Chapter 3]**

  The innovation charter articulates the goals of the design project and establishes the boundary condition for the project. The charter was used to focus discussions and workshops.

- **Generate and sense many opportunities** **[Chapter 4,5,6]**

  Market opportunities refer to particular industry needs and not to any specific solution. Market opportunities were brainstormed with forestry researchers and autonomous systems experts during collaborative workshops.

- **Screen opportunities** **[Chapter 6]**
  The opportunities were selected by means of a voting system during workshops. These opportunities are described in Chapter 6. Voting was based on the desirability, viability and feasibility framework. This down selection framework is illustrated in Figure 5 and is commonly associated with the 'Design Thinking' methodology initially made famous by the design firm IDEO[13, 14].

- **Develop promising opportunities** **[Chapter 6]**
  For each promising idea, additional background research was conducted to further validate the desirability, viability and feasibility of each opportunity.

- **Select exceptional opportunities** **[Chapter 6 and 7]**
  A second round of opportunity down selection was conducted in order to narrow the scope to the top three opportunities.

- **Reflection** **[Chapter 8]**
  A reflection on the opportunity identification results and process is provided at the end of this thesis in Chapter 8.

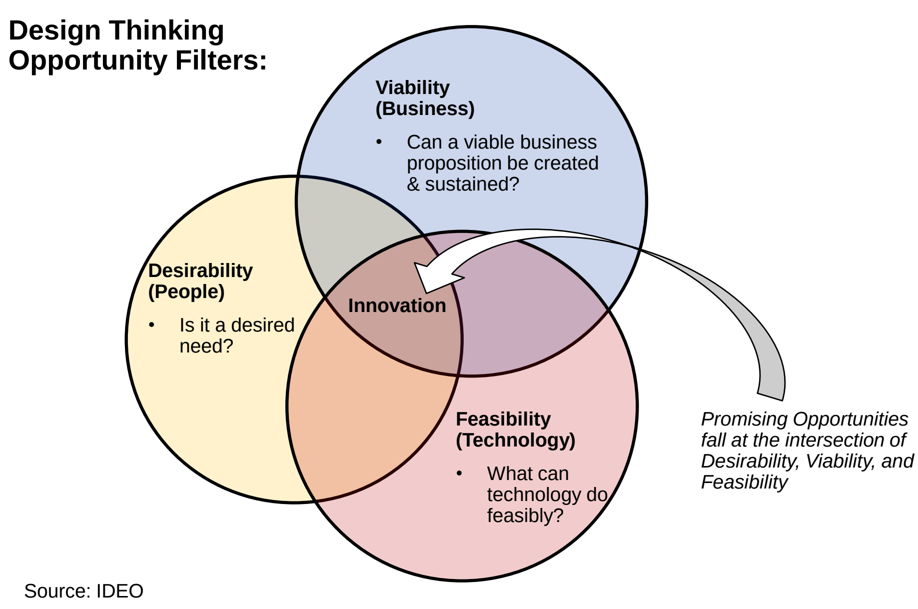


Figure 5 – Market Opportunity Selection Filters by Design Firm IDEO [13, 14]

Concept Development Phase

The concept development phase involved ideating and developing solutions to top–ranking market opportunities. The overall concept development phase as outlined in 'Product Design and Development' [10], follows a seven–step iterative process; however, only part of this framework was followed, given that finalizing specifications, building and testing a prototype were deemed out–of–scope.

The concept phase began with an in–depth study of the needs of the target market and customer, identified through conversations with forestry experts and research into the forest management industry.

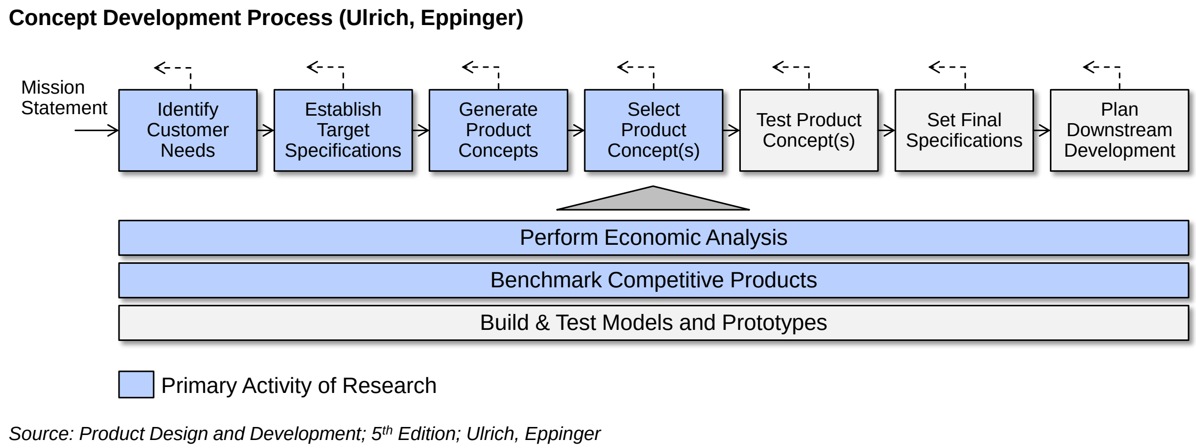


Figure 6 – Seven-Step Concept Development Process by K.T.Ulrich and S.D.Eppinger[10]

Identifying Customer Needs

Customer needs are expressed as statements that capture the desirable capabilities of the system [10]. The list of needs describes the attributes of the system elicited by interviewed customers in the target market. Not all the identified needs may be technologically or economically feasible, and inherently there will be trade–offs in the design process.

Before interviewing industry experts, it was useful to first design a generic requirements tree for an autonomous system, as illustrated in Figure 7. A similar tree is proposed in the report "reconnaissance surveillance vehicle" Sakamoto 2004[15].

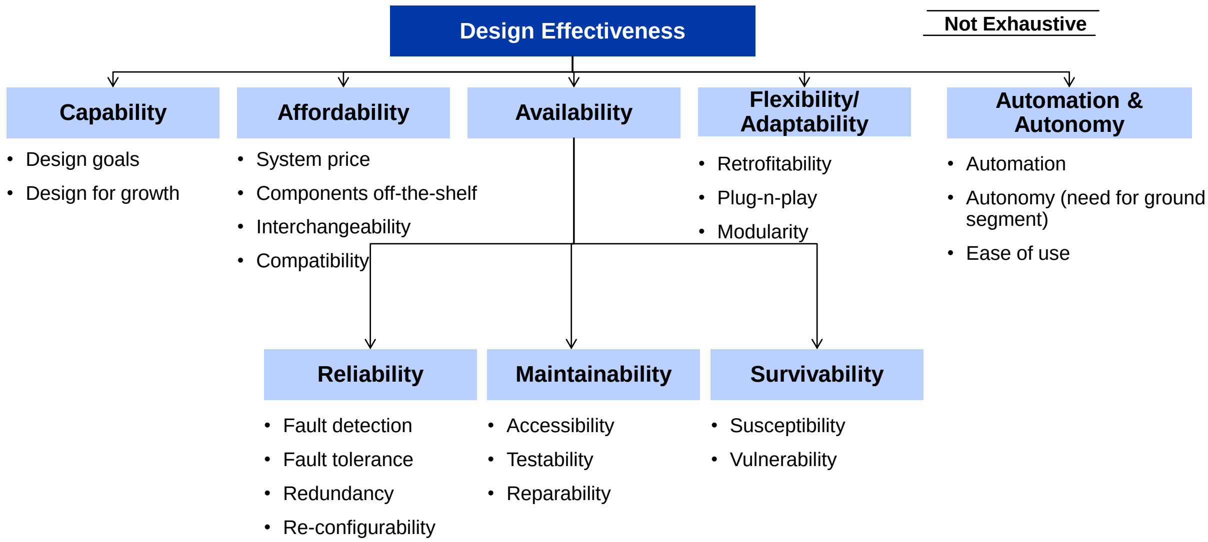


Figure 7 – Illustrative System Requirements Tree – Adapted from Sakamoto[15]

Designing the System

The system-level design phase includes the definition of the product architecture, decomposition of the product into subsystems and preliminary design of components. Whilst a detailed system level design is considered out–of–scope for this project, it is useful to preview common approaches and how they relate to the development of an autonomous system product. The output of this phase usually includes a geometric layout of the product, a functional specification of each of the product's subsystems, and a preliminary assembly and manufacturing strategy.

The system level design phase is often associated with multiple design trade–offs with regards to meeting the desired customer needs and balancing with price requirements. There are many potential approaches to evaluating design trade–offs for an autonomous system. For example, one approach is illustrated in Figure 8. The trade–off methodology of Figure 8 is a modified version of the approach highlighted in the report "reconnaissance surveillance vehicle" Sakamoto 2004[15] for the design of military UAS systems. The methodology attempts to balance Design Utility (U), Development Risk (R) with Average Procurement Unit Cost (APUC).

Evaluating Competing Designs

Design Utility is a measure of how well the system design meets the specified goals or customer requirements. Design Utility is often expressed in mathematical terms as a function of the actual performance versus desired performance as expressed by Equation 1. A Design Utility of 100 per cent means that all functional requirements/specified goals can be met by the proposed system design.

$$\text{Design Utility} = f(Actual\ performance, Desired\ Performance)$$

$$\text{Design Utility} = \left(\frac{A_{Actual}}{A_{Goal}}\right)^{p} \times \left(\frac{B_{Actual}}{B_{Goal}}\right)^{q} \dots \left(\frac{C_{Actual}}{C_{Goal}}\right)^{r} \times {P_S}^{m} \times \eta_{flex}$$

Equation 1 – Design Utility for Autonomous System

A =Objective 1 i.e. coverable area per day (acres)

B = Objective 2 i.e. LiDAR point density (points per m^2)

C = Objective 3 i.e. Maximum measurement error (range resolution in mm)

P_S = Survivability i.e. %probability of incident per mission

m = Number of missions per time frame i.e. missions per year

η_{flex} = System flexibility or usability i.e. qualitative <= 1

p, q, r = Weighting exponents <= 1

Project Risk

Project Risk is a measure of all underlying risk that may jeopardize the success of the project. Risk can be broken down in a number of ways, such as schedule risk, technical risk, cost risk, supplier risk, etc. Similarly, risks can often be numerically defined and expressed in mathematical terms.

$$\text{Risk} = f(Schedule\ Risk, Technical\ Risk, Cost\ Risk)$$

Equation 2 – Risk for Autonomous System

Average Procurement Unit Cost

Average Procurement Unit Cost (APUC) is a measure of the total cost per unit of a system. Total procurement cost includes all recurring and nonrecurring costs associated with production of the system such as hardware/software, systems engineering (SE), engineering changes and warranties, in addition to the costs of procuring technical data, training, support equipment and initial spares. If the APUC of a proposed system design exceeds the willingness to pay of the average customer, then the system design may be considered economically unviable.

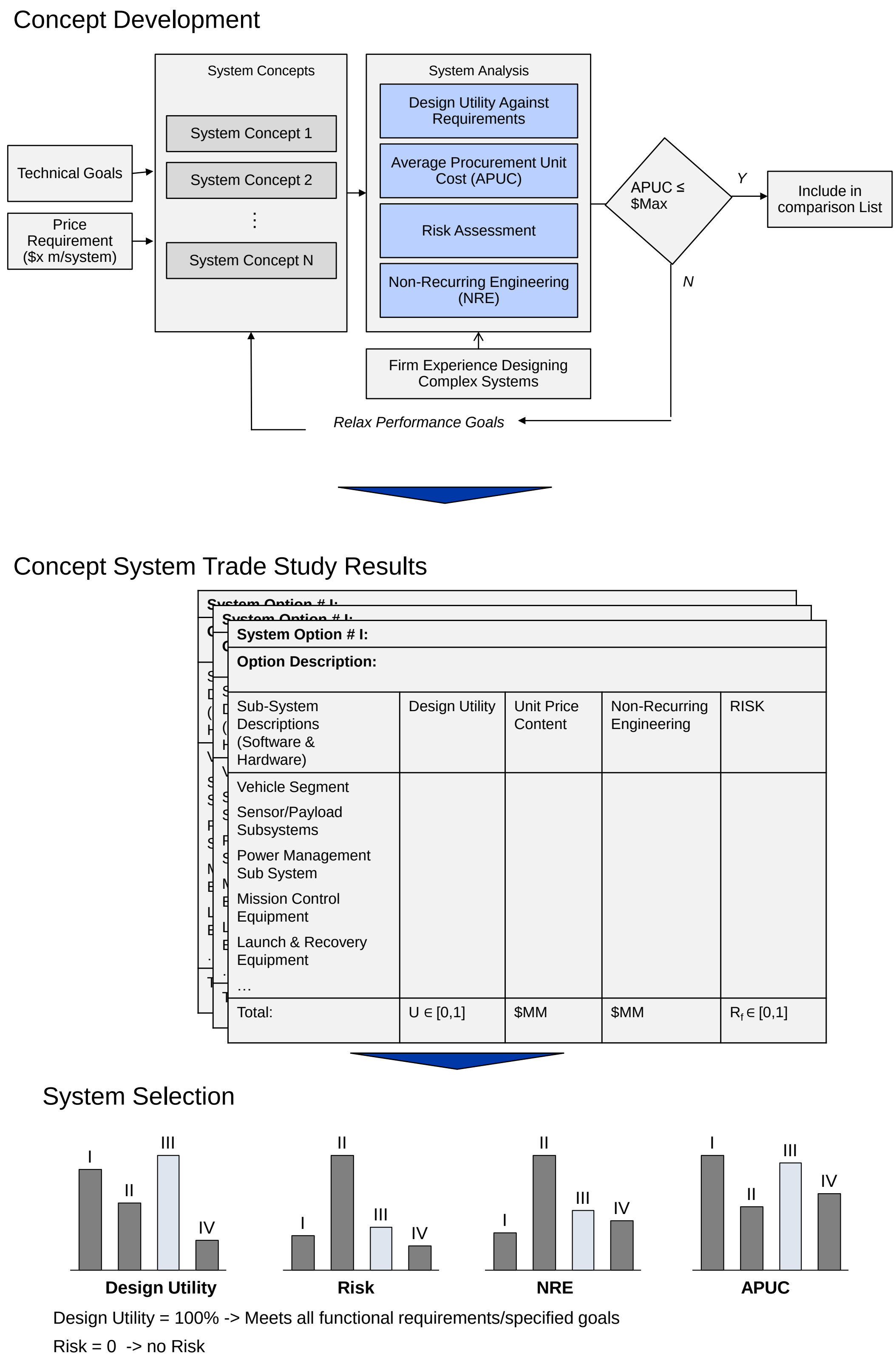


Figure 8 – Design Process for Complex System – Adapted from Sakamoto 2004[15]

Figure 8 illustrates one potential iterative system level design approach. A set of N potential designs are developed. For each design, an analysis of Utility, Risk, APUC, and Non–Recurring Engineering Costs (NRE) is assessed. Designs that exceed the maximum allowable per unit cost are either dismissed or re–evaluated based on relaxing performance objectives. Detailed system trade studies are conducted for each potential design. In Figure 8, Design Option III is considered the best option with greatest design utility, low risk, and low development cost (NRE).

2.2 State–of–The–Art System–of–Systems Design Methods

Multi–Attribute Tradespace Exploration

In terms of 'state–of–the–art' methods pertaining to the design and development of autonomous system solutions, the Multi–Attribute Tradespace Exploration method (MATE) is a promising new approach [16, 17]. The method was first proposed by researchers at the Massachusetts Institute of Technology and the Charles Stark Draper Laboratory. The methodology attempts to address a number of issues faced by traditional heuristic approaches (such as the method described in section 2.3), by attempting to quantify disparate design parameters and disparate stake–holder needs, into a common tradespace to allow the consideration of a larger and more complete set of design alternatives[17, 18].

One of the greatest advantages, but also greatest challenges, of autonomous systems technologies is their incredible flexibility. For example, a particular surveillance challenge may be solved using several disparate technologies: satellite, aircraft, unmanned air vehicle, swarms of unmanned air vehicles, and fixed sensor networks. All of the above technologies and combinations thereof, represent possible system concepts to achieve the same surveillance mission objectives. Traditional system level design approaches struggle to quantify differences in the approaches with respect to stakeholder requirements. Multi–Attribute Tradespace Exploration enables such disparate systems concepts to be compared on the same 'tradespace', enabling decision makers to quantitatively compare disparate systems concepts on a common performance and cost basis. The paper 'Demonstration of System–of–Systems Multi–Attribute Tradespace Exploration on a

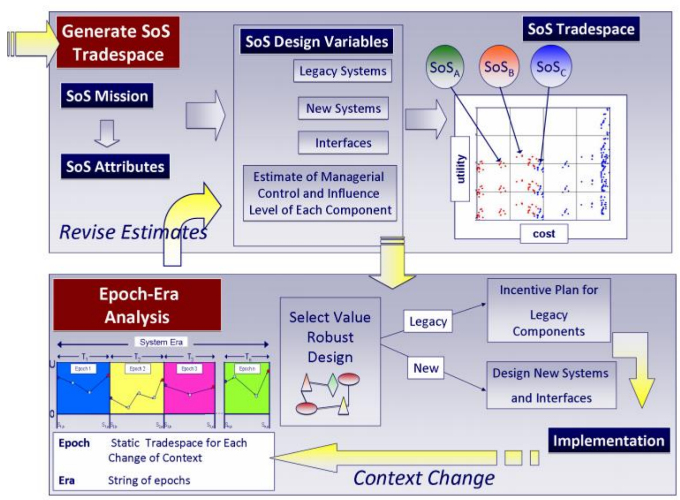


Figure 9 – System-of-System Tradespace Exploration Method[19]

Multi–Concept Surveillance Architecture'[19] demonstrates the approach by employing the Multi–Attribute Tradespace Exploration method to the design of a disaster surveillance system.

Whilst the application of the Multi–Attribute Tradespace Exploration method to this work is out–of–scope, it is worth mentioning here as a potential area for further investigation.

Selecting Levels of Automation and Levels of Autonomy

An important design challenge when developing a new autonomous system is deciding on the most efficient level of automation and autonomy. In general, as automation and autonomy increases, so does the particular design utility, however, so does the project risk and development cost. Therefore, there are inherent design tradeoffs that are unique to autonomous systems that must be considered in any–state of–the–art design methodology. As of yet, the multi–attribute tradespace framework does not explicitly address possible levels of automation and autonomy.

Based on a literature review, theory regarding the efficient choice of automation and autonomy for autonomous systems is still in its infancy and should be considered an important area for future research. In this section we describe a few general considerations based on the little available literature and discussions with automation experts.

Levels of Automation

When defining automation, we refer to the required degree of human supervision or input as illustrated in Figure 10. In supervisory control, a human operator monitors a system and intermittently executes some level of control on a process, acting on some subset of automated agent in the system. For example, a controller may undertake one or more of the following actions as defined by Sheridan 1992[20, 21]:

- Develop and input the desired plan for the mission
- Monitor the execution of the plan
- Intervene when the system makes a mistake or requires assistance
- Learn from past errors and experience and adapt the system

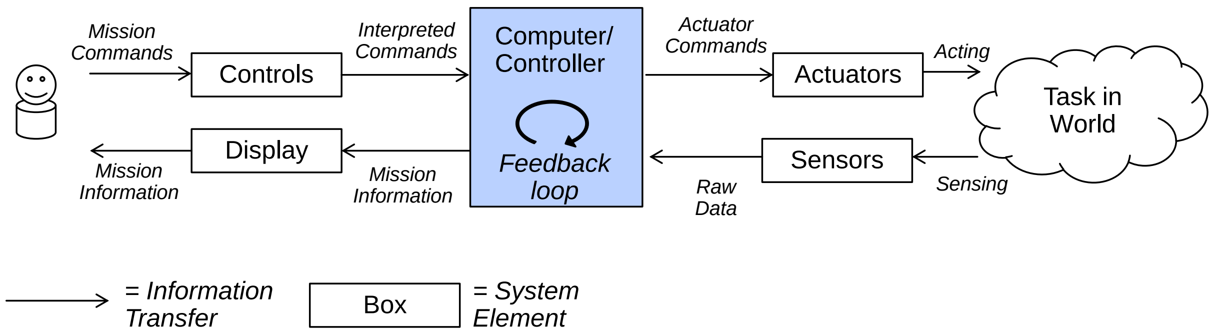


Figure 10 – Human Supervisory Control Architecture – Adapted from Sheridan, 1992 [21]

In supervisory control of autonomous systems, various levels of automation can be introduced into the decision support system. A system may be described as fully automated when an operator is not required in the decision process, and described as minimally automated when the operator provides most or all of the control input with little to no assistance from the computer controller. When designing a new system, it is often a challenging task to articulate how automated the design is. As a starting guideline, Sheridan & Verplank 1978[22], propose the following set of discrete and generic automation levels that can be adapted to any decision support system, including most autonomous systems.

Table 1 – Levels of Automation – Sheridan & Verplank 1978 [22]

Increasing Automation

Level	Automation Description
1	Computer offers no assistance: human must take all decision actions.
2	The computer offers a complete set of decisions/action alternatives or …
3	Narrows the selection down to a few,or …
4	Suggests one alternative, and …
5	Executes that suggestion if the humanapproves, or …
6	Allows the human a restricted time to veto before automatic execution, or …
7	Executes automatically, then necessarily informs humans, and…
8	Informs the human only if asked, or …
9	Informs the human only if it, the computer, decides to.
10	The computer decides everything and acts autonomously, ignoring the human.

Levels of Autonomy

In the paper "Human Supervisory Control of Swarming Networks" by Cummings 2004[9], it is argued that another dimension of automation, beyond the standard human–computer interaction described above, is possible in complex autonomous systems. In particular, systems that involve multiple interacting agents/nodes, such as individual UAS in a swarming network, require additional automation related to intra–vehicle autonomy. We refer to this intra–vehicle related automation as the systems autonomy.

Cummings proposes that autonomy can be similarly described by discrete and generic levels as defined in Table 2. At the minimum level of network autonomy, there is essentially no collaboration between system agents/nodes. At the maximum network autonomy, agents are in full collaboration and need no human intervention for emergent behavior[9]. Cummings argues that autonomy can be independent of automation. For example, it is possible to have a system with high autonomy (i.e. vehicles remain in a cooperative formation at all times), but with little independent decision making capability/automation (i.e. human remains in control at all times to direct the swarm).

Table 2 – Levels of Autonomy – Cummings 2004[9]

Increasing Network Autonomy

Level	Network Autonomy Description
1	Vehicles/Nodes do not communicate with one another and follow original tasking unless human identifies a new task
2	Vehicles communicate with one another for separation and threat deconfliction but still depend on human for new tasking.
3	Vehicles collaborate with one another and the human only interacts with the “lead” unmanned vehicle.
4	Vehicles are in full collaborative communication, and individual vehicle tasking changes according to a predetermined algorithm. There is no human intervention

Identifying Efficient Levels of Automation and Autonomy

Research into identifying efficient levels of system automation and autonomy is still relatively new. Much research has been conducted into determining what levels of automation promote efficient human computer interaction in simple decision control systems[20], however, little research has been conducted on the human–interaction with swarming autonomous systems[9]. Furthermore, little research links designated automation and autonomy to the systems economics. The thesis “Business Case Assessment of Unmanned Systems Level of Autonomy” Liu 2012[23] makes an initial attempt at developing a framework for evaluating autonomy and automation.

In the section we propose a simple and more generic four-step process to identifying efficient levels of automation and autonomy.

Step 1: The first proposed step when deciding on the efficient level of automation and autonomy is to articulate the objective for the automation. In particular:

I. *Value of operator time*: Increasing levels of automation and autonomy may reduce the level of human input required to achieve a particular objective
II. *Value of operator skill*: Increasing levels of automation and autonomy may reduce the skill level or training required to operate the system
III. *Value of system flexibility*: Increasing levels of automation and autonomy may increase the range of applications to which the system may be applied. Note that in some cases increasing levels of automation may also reduce the system's flexibility
IV. *Value of human safety*: Increasing levels of automation and autonomy may protect the human operator from the need to venture into a potentially hazardous environment
V. *Value of reliability, safety, or other*: Increasing levels of automation and autonomy may increase the reliability, system safety, or other desirable feature of the system

Step 2: The second step to evaluating automation and autonomy is to articulate the feasible design levels. Table 1 and Table 2 may act as an initial guideline for defining the possible levels of automation and autonomy; however, these generic definitions may need customization to the specific application.

***Step 3*:** The third step is to identify the potential R&D investment required for the various levels of automation and autonomy.

One proposed method for evaluating the R&D complexity is to break down the Human Supervisory Control Architecture of Figure 10 into component automation tasks. The textbook "Introduction to Autonomous Mobile Robots"[8] proposes a reference architecture involving the following component tasks: path planning, path execution, localization and map building and information extraction. In Figure 11 we combine the supervisory control architecture of Figure 10 with the autonomous mobile robot architecture to better understand the different aspects of automation and autonomy.

The levels of automation can be broken down into levels of complexity for each of the four component automation tasks. Some component tasks are more difficult to automate than others. For example, many perception tasks involved in the information extraction step of Figure 11 may be more challenging than the other three components. In fact, many perception problems have not been solved and may be impossible to fully automate with today's technology[8]. Breaking down the various levels of automation into the four automation tasks can thus better inform the overall R&D challenge and thus estimated investment required.

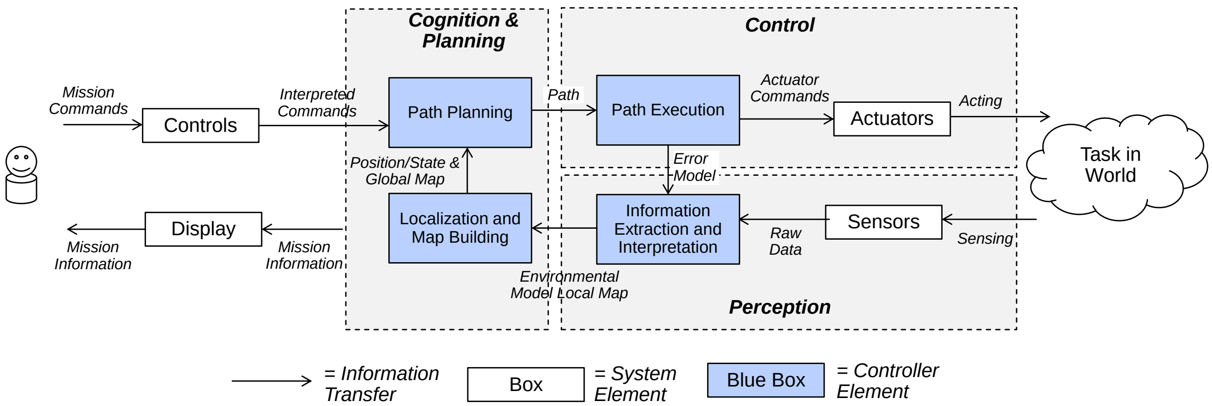


Figure 11 – Revised Human Supervisory Control Architecture

Step 4: The fourth step involved in the evaluation process is to quantify the link between the defined levels of automation and autonomy with the automation objectives defined in Step 1.

Figure 12 helps to illustrate Step 4 in graphical form for a generic forestry application. On the left hand axis we use the metric of "number of human operator hours required per unit area of forest surveyed" as the primary value metric. As automation and autonomy increases, the number of human operator hours decreases in discrete intervals. On the right hand axis, we define the cost of increasing levels of automation and autonomy by the associated R&D and production costs. As automation and autonomy increases, the cost per system increases as a stepwise function. The economic design optimum may be considered as the intersection of these two functions.

In Figure 12 we also define a level of automation corresponding to the minimum viable product. When designing any new product it is important to identify the minimum level of functionality required for any early adopter to purchase. This minimum is often referred to as the minimum viable product. For an autonomous system, the minimum viable product consists of both a minimum level of functionality and a corresponding minimum level of automation and autonomy. The first product release should in theory be designed to the minimum viable product specification in order to minimize risk. Subsequent product generations and releases should progress towards the economic optimum level of automation [24].

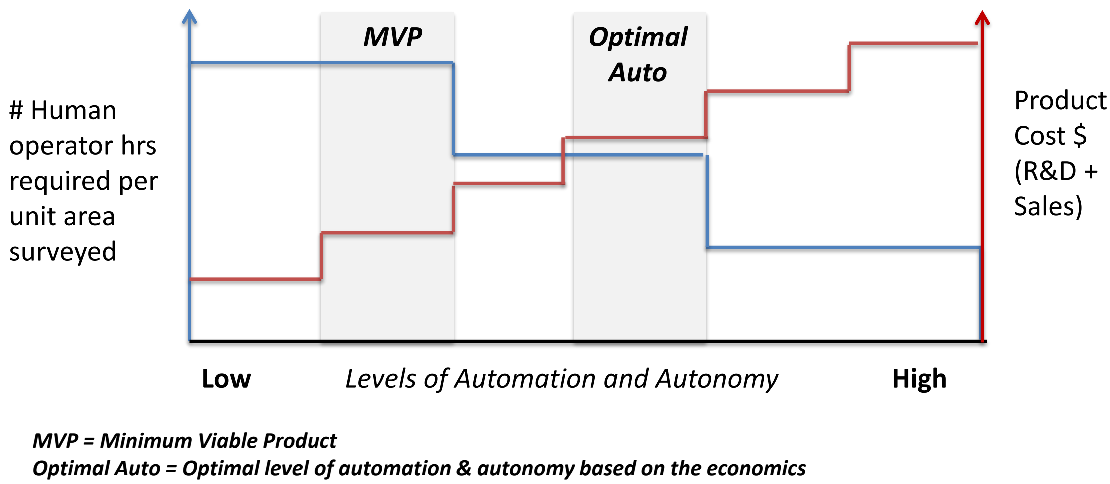


Figure 12 – Design Trade–offs as a Function of Automation and Autonomy

3 Project Charter and Scope

The innovation charter articulates the goals of the design project and establishes the boundary conditions for the project. The final charter and scope for this research was agreed as:

"To identify product concepts for the North American commercial forestry management market that assist monitoring and inventory analysis activities, utilizing existing autonomous systems technologies."

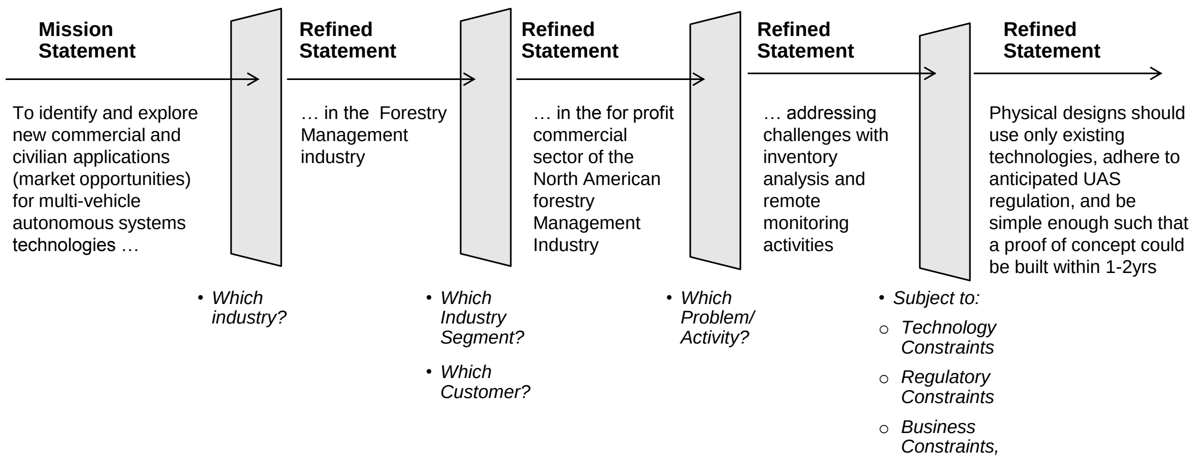


Figure 13 – Refinement Phases of the Mission Statement

3.1 Identifying the Target Market and Defining Project Constraints

Which Industry?

The forestry industry was selected as the primary focus for this study for three reasons:

1. Based on estimates by industry experts[5], the forestry and agriculture industry is expected to become the third largest market for commercial and civilian unmanned systems – see Figure 14.
2. A number of companies are attempting to address market needs in the two largest expected segments, including government and fire services, and precision agriculture. In contrast, little work has been conducted on the application of autonomous systems to forestry management.
3. Based on preliminary discussions with a leading US forestry management company, there is an expressed need and interest in developing autonomous systems technologies for the forestry industry. This need is driven by growing pressure to increase productivity and reduce costs associated with monitoring and nurturing millions of acres, as a result of increased international competition and emerging environmental challenges[25].

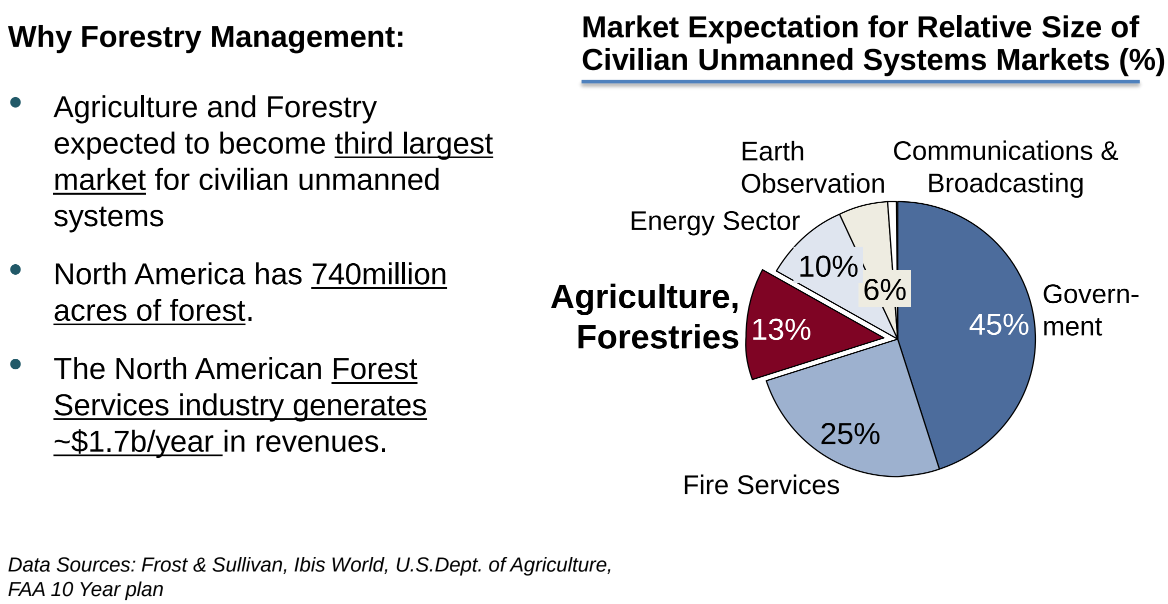


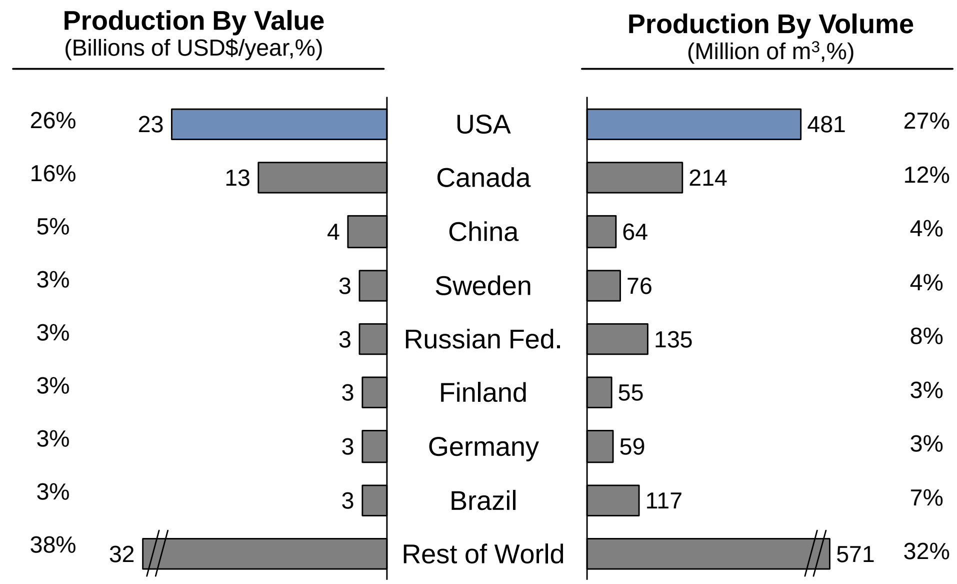
Figure 14 – Civilian and Commercial Autonomous Systems Market by Projected Relative Shares

Which Geographic Boundary, Industry Segments, and Target Customer?

Based on data presented in Figure 15 and Figure 16, the North American commercial forestry management market was selected as the primary focus for this thesis. The USA and Canada are the two largest producers of timber by value in the world, accounting for approximately 40 per cent of the world industrial roundwood market by value (Figure 15).

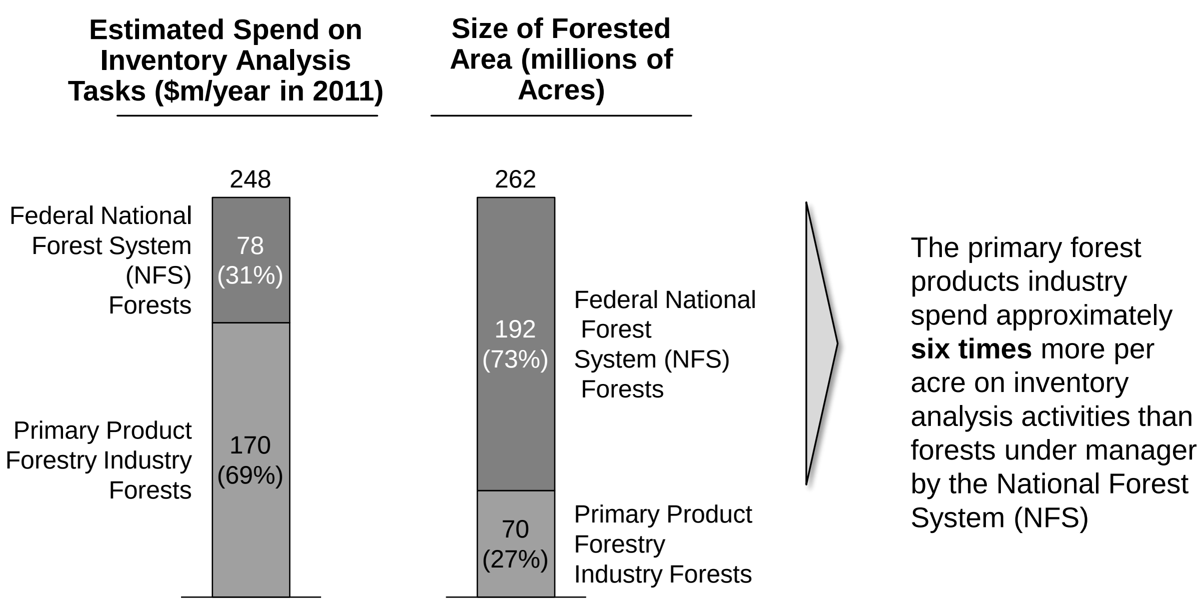
The forestry industry in the USA and Canada are deemed early adopters for new forestry technologies when compared with the rest of the world. For example, due to technology and sophisticated management practices, the USA is nearly eight times more productive, in terms of employees per m^3 of timber produced, than Russia, the third largest timber producing country by value – see Figure 17. Thus, although government regulations involving the use of unmanned autonomous systems are more stringent in North America, the success of any new advanced forestry management product will be reliant on North American adoption.

Whilst there is a significant need for improved technologies in public forestry management, the commercial segment outspends the public sector by approximately 6 to 1 per acre on forestry monitoring activities. Therefore, the private commercial sector was designated as the primary focus.



Source: FAOStat Report 2010

Figure 15 – Industrial Roundwood Production by Top Producing Countries



Data sources:
(1) FIA Financial Report 2011
(2) U.S Environmental Protection Agency, Facts and Figures; www.epa.gov/oeacaagct/forestry.html
(3) Ibis Reports: 11311, 11331, 11531, 23111, 32121, 32191, 32199b, 32211

Figure 16 – U.S. Forest Inventory Analysis Funding vs. Commercial Forestry Sector

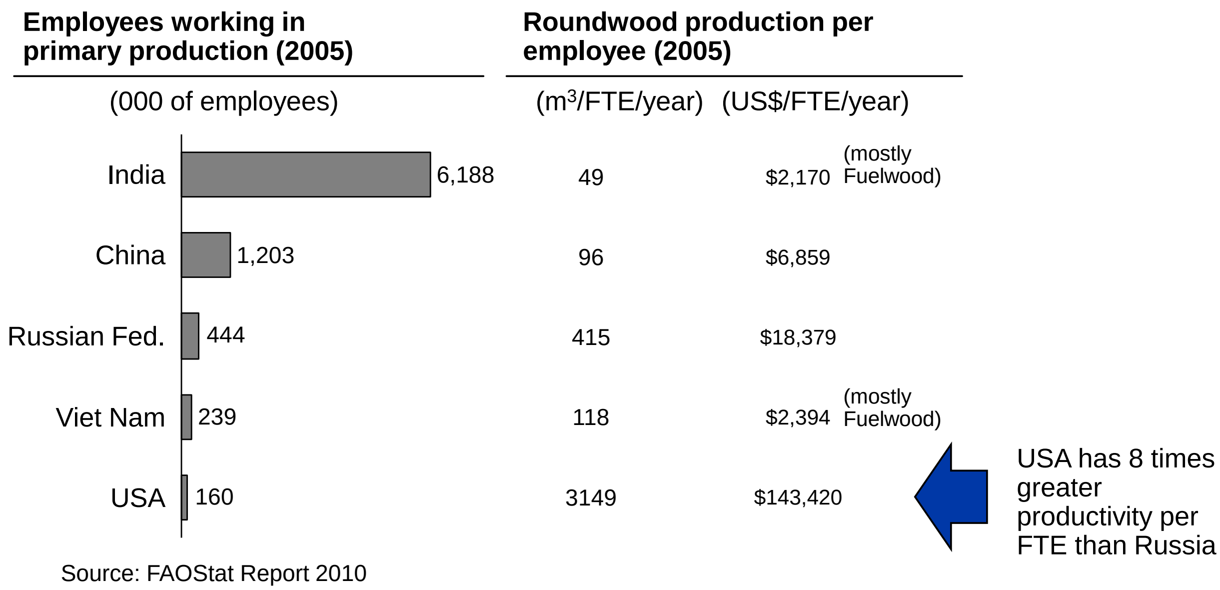


Figure 17 – Employees Working in Forestry

Which Activities?

Remote monitoring and inventory analysis, including the detection of insects and disease, was selected as the primary focus of investigation.

Based on qualitative discussions with forestry experts, remote monitoring and inventory analysis involve high value activities that could benefit from autonomous systems technologies – see Chapter 6 for additional discussion.

Based on rough estimates, forest monitoring and inventory analysis services roughly account for approximately 40 per cent of the $1.7 billion forestry services market in the United States alone. This includes both remote monitoring and field data collection for Timber Resource and Mapping, Forest Pest Control, and Forest Science Research – see Figure 18.

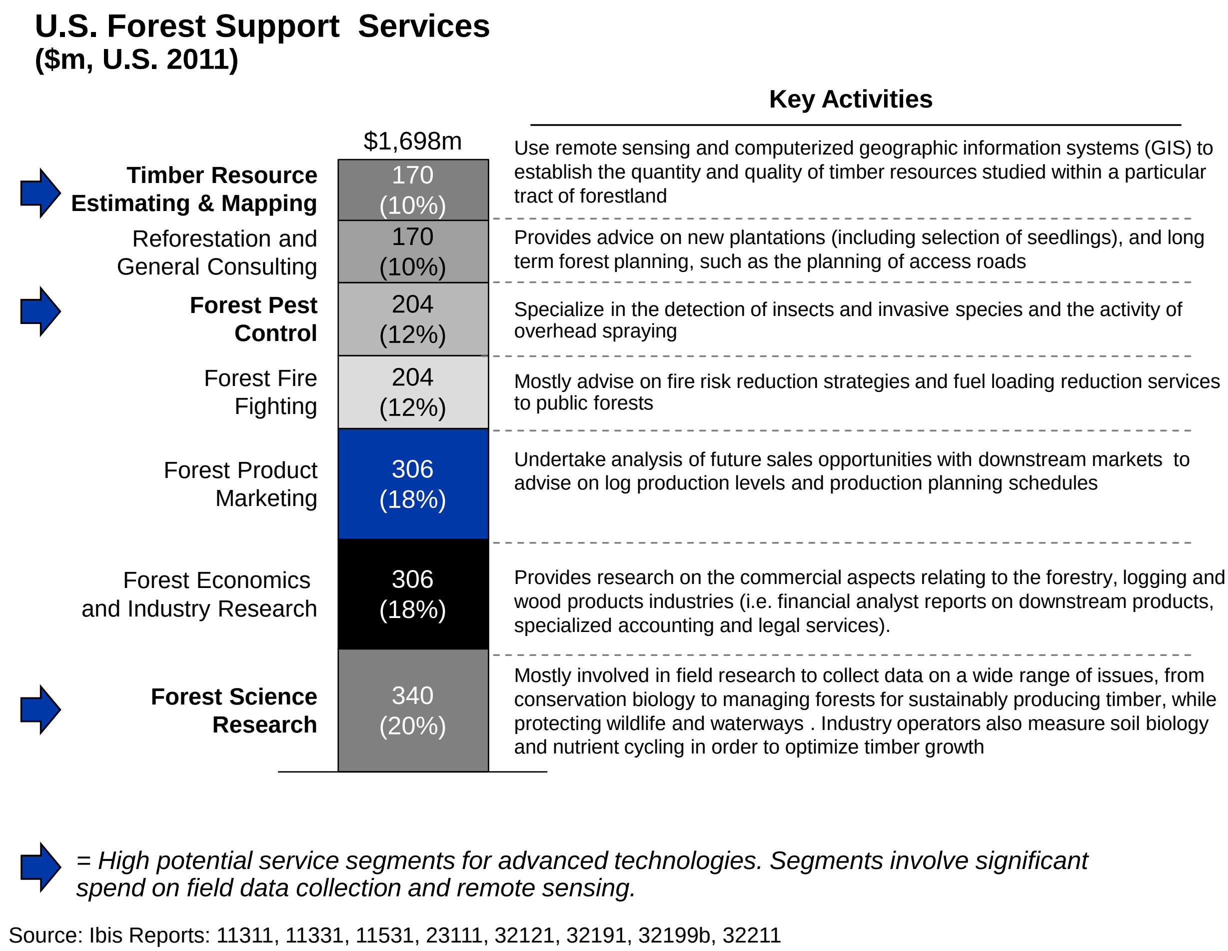


Figure 18 – U.S. Market for Forest Support Services

Subject to What Constraints: Technology Constraints, Regulatory Constraints, Business Constraints

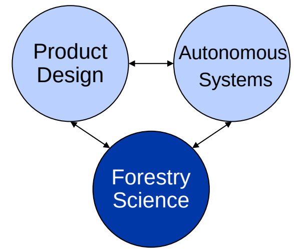
Whilst no strict constraints were enforced during the concept development phase of this project, it was useful to enforce a few commonsense limitations:

- **Technology:** Concepts systems must only use existing technologies or capabilities. Early stage technologies were allowed during concept ideation, subject to evidence of active development and testing in the academic community, and subjective opinion by autonomous systems subject matter experts.
- **Regulatory:** Concept systems should not include technologies that will be restricted by government legislation for the foreseeable future. For example, the use of high altitude unmanned

autonomous systems (UAS) will continue to be prohibited under the proposed 2015 Federal Aviation Administration regulations involving the integration of UAS into National Airspace.

- **Timeline:** Ideally, the concept designs should be simple enough for a proof of concept to be developed within a two–year window, subject to appropriate resourcing and funding.

4 Industry Review – Forest Management



Forestry management is a complex and evolving science and practice with vast scope. This chapter aims to introduce forestry management, and more generally, the forest products industry. By analyzing the various segments, activities, stakeholders, and technology trends, we highlight the most appealing sub–segments for innovation – our 'beach head' market. Furthermore, by reviewing common forestry management activities and practices, we develop an understanding of where new technologies may be applied. For a more comprehensive introduction into forestry management, the reader is referred to an introductory textbook such as: 'Introduction to Forest Science'[26] or 'Global Forest Resource Assessment 2010'[27] published by the United Nations Food and Agriculture Organization.

4.1 Industry Structure and Market Trends

Defining Forestry Management

Forests cover a third of our planet's land area[27], or approximately 40 million km^2. Forests provide raw materials, maintain biodiversity, protect land and water resources, provide recreational areas and play a critical role in climate change mitigation. At the same time, forests are affected by fire, pollution, pests and invasive species, and are often the primary targets of agricultural and urban expansion. Forests are heavily exploited, and it is becoming increasingly important to manage them more sustainably.

Forestry management is the science and craft of creating, managing, harvesting, conserving and repairing forests and associated resources in a sustainable manner[26]. A forester is a person (typically with a university qualification) who practices this science. Foresters engage in a broad range of activities, including timber harvesting, ecological restoration and management of protected areas.

In North America, the predominant activities of a forest manager may vary depending on the objectives for the forest: whether the forest is publicly owned and designated for recreation and/or preservation, or whether the land is managed for commercial timber production. As outlined in Chapter 3, the primary target area of investigation for this research is the commercial forestry sector and thus we will consider only the associated commercial forestry tasks.

The Forest Products Industry

The forest products industry is a multinational industry with plantations and mills around the world. With over 44,000 facilities in the United States alone (6,541 in Pulp and Paper and 37,471 in Lumber and Wood), the industry employs close to 1.3 million people in all regions of the country, and ranks among the top 10 manufacturing industries in 46 states[28].

The forest products industry value chain is illustrated in Figure 20. The value segments are defined according to the North American Industry Classification System. Forestry companies may compete in one or many value segments. For example, the largest forestry companies in the United States, such as Plum Creek and Weyerhauser, are vertically integrated throughout the value chain.

Forest managers operate in the Timber Services segment of the forest products value chain. Forest managers may manage a timber stand on behalf of the land-owner or may contract the land but own the timber they grow. That is, a forest manager may sell directly to the logging industry without owning the land. Large commercial operators such as Plum Creek and Weyerhauser often manage significantly more land than they own.

Once the timber is felled, the logging company takes possession and is responsible for cutting, temporarily storing and transporting the timber to the primary processing facilities: sawmills or pulp mills. Whilst there are many opportunities for advanced technologies in the logging industry, this industry segment is deemed out–of–scope. Established heavy equipment manufacturers such as John Deere and Caterpillar Forestry make significant research and development investments each year with respect to advanced logging technologies.

Figure 19 - The Forest Machine - A Past R&D Project by John Deere

The Forest Support Services industry is an adjacent industry that provides consulting services to forestry management companies. In particular, this industry may provide services such as timber resource estimation & mapping, reforestation consulting, pest control service and many more services. A forest support services company may own expensive aerial remote sensing equipment such as light detection and ranging and multispectral imaging equipment. The support services segment has greater revenues than the timber services segment based on how industry revenues are classified by the North American Industry Classification System.

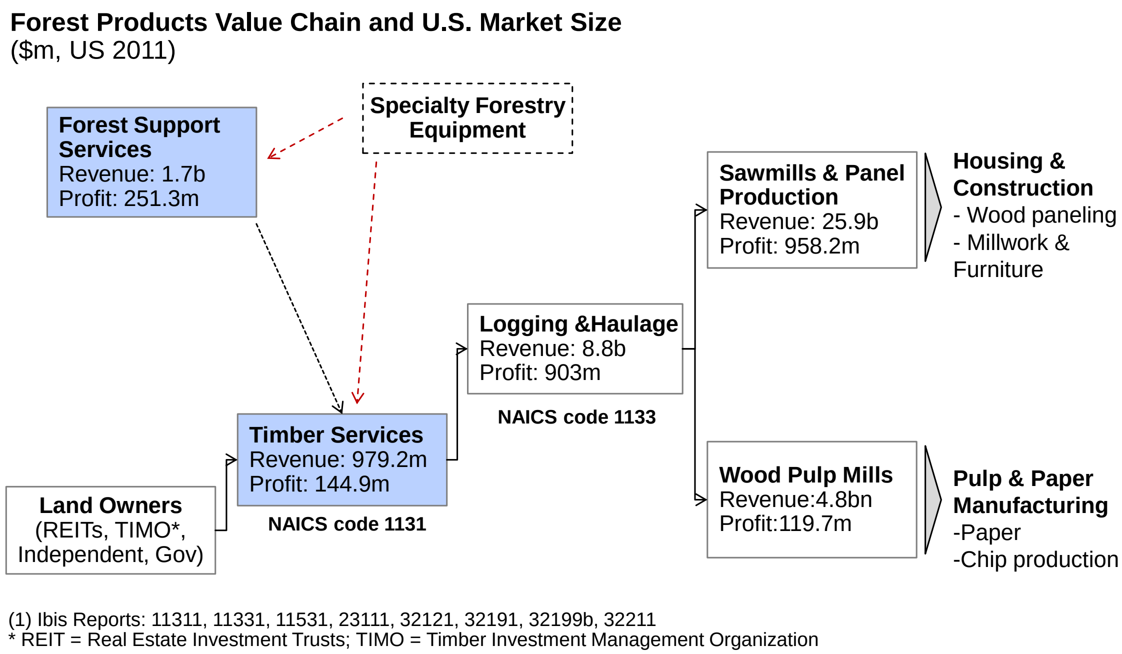


Figure 20 – Forest Products Value Chain [29–33]

Important Forestry Stakeholders

Forest management companies and forest support firms were established as the two target customers for new technology innovations. Forest managers conduct a significant portion of their data collection by sending foresters into the field to conduct an inventory. Furthermore, service companies, such as those that own expensive remote sensing equipment, were also deemed potential customers for new forestry technologies. The extended list of stakeholders that regularly collect, use or commission forestry data is listed in Figure 21.

Stakeholders that actively use forestry data

Stakeholder	Description	Typical Concerns:
Private Timberland Owners	Private or Industrial investment groups, with a focus on maximizing returns on their timberland investment.	• What is the net value of my land or timber holding? • What are my expected cash flows?
Forest Managers	Hired by Timberland owners (public and private) for the everyday operations of the forest: planning, maintaining, and harvesting. Manager may include: • *Silviculturist* • *Arborist* • *General Forester* • *Lumberjack*	• What activities (i.e. stand improvements) should be undertaken to maximize overall growth and forest value? • Do I have a pest of disease problem? • When should a stand be harvested?
Forest Service Companies	Hired by timber managers to conduct a variety of consulting service such as aerial remote sensing services	• What is the demand for aerial remote sensing services?
Logging Companies	Buy standing timber from timber management companies for felling and sale downstream to sawmills and pulp mills	• Is this timber stand worth the amount asked?
Federal/State Forest Agencies	Public landowners looking to ensure the sustainability of public forests whilst providing safe access for recreational use	• How much forest exists? • What are the impacts of recreational use? • What are the risks of wildfire?
Environmental Researchers	Entities interested in environmental research, including universities, and government policy researchers/advisors	• How is the forest health changing in response to anthropogenic factors? (i.e. climate change)
Law Enforcement	Law enforcement agencies with jurisdiction over forested lands	• Are there illegal drug plantations present?
Fire Departments	Fire protection agencies with jurisdiction particularly near the wild-land urban interface.	• What is the level of forest fuel loading?

[dashed box] = Primary Customers of Forest Management Technology

Figure 21 – Forestry Stakeholders

In the United States, 70 million of the roughly 480 million acres of timberland belong to large industrial forestry companies. Whilst this only represents 14 per cent of the total US timberland, over 33 per cent of US commercial timber by volume is produced by these select few companies – see Figure 22. Roughly 65 per cent of industrial timberland is owned and managed by the 20 largest firms listed in Figure 23. The largest of these firms represent our target market. These include Plum Creek, Weyerhauser, Forestland Group, and Campbell Group, being the four largest companies. During this research, interviews were conducted with a number of representatives from the above stakeholder list.

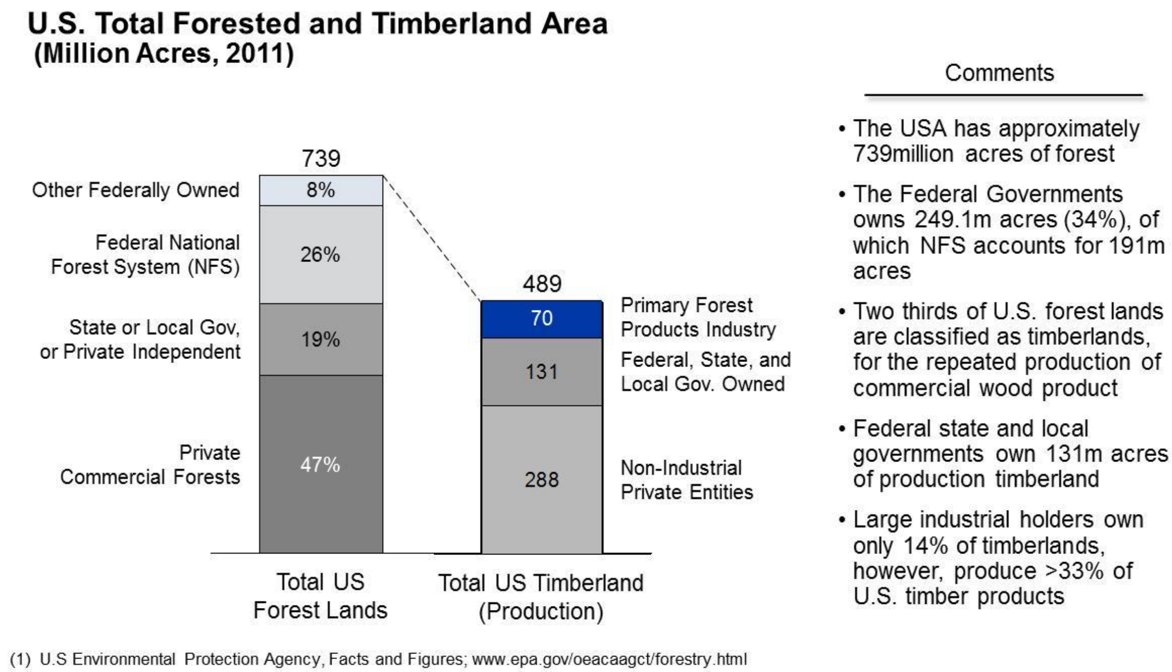


Figure 22 – US Forest Lands by Ownership and Application

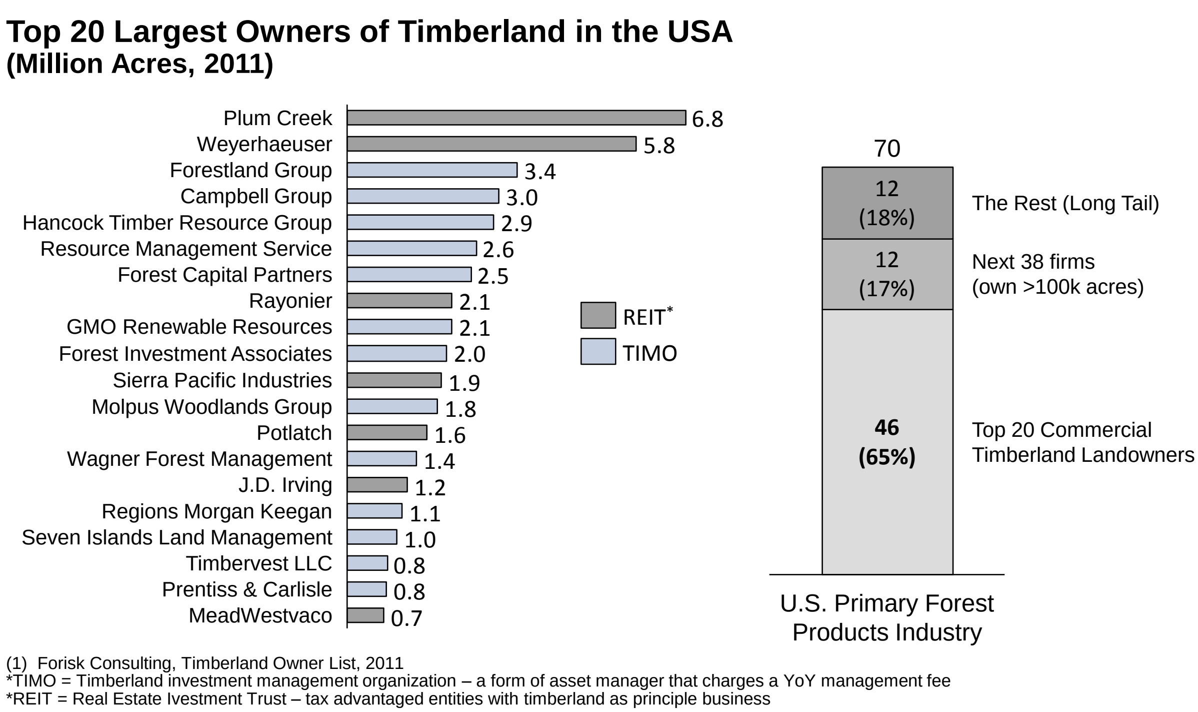


Figure 23 – Top 20 Industrial Forestry Companies in the USA [34]

In addition to the above companies, the largest forestry support services companies were also considered as potential customers. The forest support services industry, however, is primarily composed of small, privately–owned firms that operate within a limited geographic region. The industry is highly fragmented, with less than a tenth of companies employing more than 20 employees[32]. The largest of the forest services companies in the United States include but are not limited to:

- American Forest Management. Inc
- Mason, Bruce and Girard Inc.
- Reynolds Forestry Consulting & Real Estate PLC
- Larson and McGowin Inc.

Source: IBIS World Industry Report 11531[29]; Desktop Research

Additionally, large photogrammetry & remote sensing firms were considered as potential customers. These companies service a range of industries beyond forestry, and own and operate expensive remote sensing and aerial Light Detection and Ranging (LiDAR) equipment. The largest operators in the United States include but are not limited to:

- Aerial Services, Inc.
- Airborne 1 Corp.
- Aerometric
- Aerotec, LLC
- Laser Mapping Specialists, Inc.
- Topographic Imaging, Inc.
- Woolpert LLP

Source: The LiDAR Exchange – The LiDAR Directory 2012[35]

4.2 Forest Management Practices (Missions)

To maximise information gain from stakeholder and expert interviews, it was important to first understand the common activities of a forest manager. In the terminology of autonomous systems, we refer to these activities as missions. This section reviews common management activities (missions), and highlights potential tasks that may benefit from technology innovation.

Most commercial foresters are trained in the art of silviculture, which is the practice of controlling the establishment, growth, composition, health and quality of forests to meet diverse needs and values. Silviculture practices may vary significantly depending on the nature of the land under management. Some factors that influence the nature of management activities include:

- Degree of management: heavily managed single species plantation vs. naturally regenerated

- Tree family: softwood (coniferous) vs. hardwood (deciduous)
- Local risk of disease, pests, fire and other

In general, silviculture practices can be categorized by the four growth phases of a forest, as illustrated in Figure 24. Heavily managed, single age, single species plantations follow these four steps relatively closely. In mixed age, naturally regenerated forests, however, activities from all four phases may occur simultaneously. Furthermore, the silviculture practices listed in Figure 24 may be practiced at various degrees of intensity, depending on the manager's yield objectives.

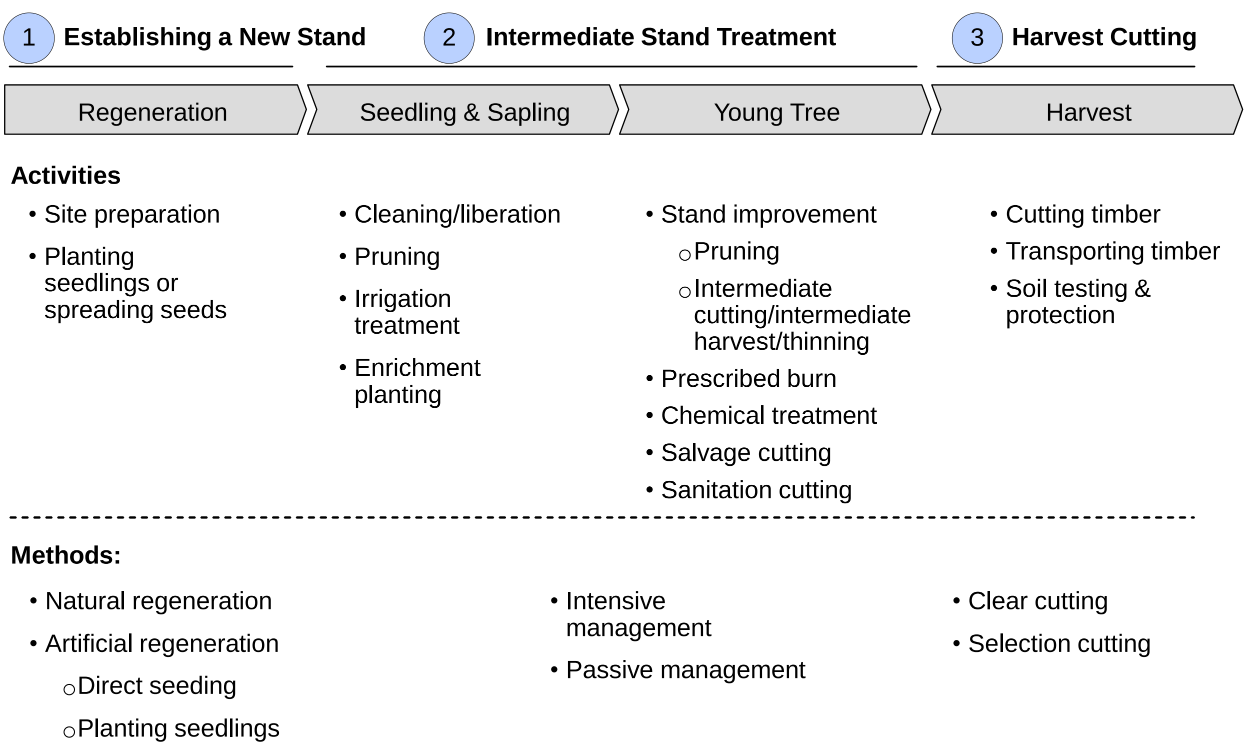


Figure 24 – Silviculture Activities by Forest Stage

Regeneration Activities

Site Preparation

Site preparation may involve up to three steps. The first step of preparation involves the removal of surface debris by either burning or mulching using a mechanical cutter. This treatment helps reduce the organic matter on the surface, enabling seeds to reach the ground, and reduces competition for seeds or seedlings. The second step involves loosening or breaking up hardened soil layers using a plough or subsoiler. A third step may involve forming furrows and beds to enable excess water to drain away in the furrows.

Artificial Regeneration via Planting Seedlings or Spreading Seeds

Depending on the species of tree to be planted, a new forest may be artificially established by either planting or spreading seeds or planting seedlings.

The practice of direct seeding involves the planting or spreading of seeds over the site to be regenerated. Seeds may be planted directly into the soil surface using mechanical equipment, spread via a tractor or dispersed via aircraft. Aerial seeding is a good method when a large area needs to be established. It is important, however, that seeding is timed to coincide with adequate soil conditions, defined by soil moisture and temperature, to ensure a good germination rate. In overly dry conditions, seeds will not germinate and may go to waste.

Seedlings are trees that are in their early stage of development. Seedlings are cultivated en masse at specialized seedling farms referred to as nurseries. When sufficiently mature, seedlings are transplanted from nurseries into a forest. Seedlings are planted directly into the mineral layer of the soil via hand planting or machine planting, which can be a laborious and expensive process.

Seedlings ready for plantation may be extracted with, or without, soil. Seedlings extracted without soil and with exposed roots are referred to as bare–root stock. These seedlings must be planted quickly. Seedlings may also come in small containers or plastic bags with soil maintained around the roots. These seedlings are referred to as containerized stock. Containerized stock typically yields a higher survival rate than bare–root stock, but can also be significantly more expensive.

The best time to plant seedlings is in the early spring, before it gets too hot and dry and after the ground has sufficiently warmed. Planting too early in the season may expose the seedlings to excessive cold that may damage the seedling or prevent it from germinating. Planting too late into the season may expose the seedling to excessive heat and poor moisture conditions.

Intermediate Stand Treatments

Cleaning/Weeding/Liberation

These terms all refer to early stand treatments intended to remove competition and improve growth. Weeding is an early treatment implemented during a stand's seedling stage, which removes or reduces herbaceous or woody shrub competition. Cleaning refers to the activity of removing select saplings and vegetation that compete with young trees. The treatment favors trees of a desired species and stem quality. Liberation cutting is a treatment that releases tree seedlings or saplings by removing older, overtopping trees.

Thinning and Pruning

Thinning and pruning are activities that are commonly carried out in an established timber stand. The goal of thinning is to control the amount and distribution of available growing space. By altering stand density, foresters can influence the growth, quality and health of residual trees. It also provides an opportunity to capture mortality and cull the commercially less-desirable trees, usually smaller and malformed.

Pruning, as a silviculture practice, refers to the removal of the lower branches of the young trees (also giving the shape to the tree), so clear, knot–free wood can subsequently grow over the branch stubs. Clear, knot–free lumber has a higher value. Pruning may or may not be performed, depending on the tree species and the objectives of the forest manager.

Prescribed Burn

A prescribed burn, as the name suggests, involves initiating a low intensity fire through a forest during the cooler months, to reduce fuel build–up and decrease the likelihood of serious hotter fires. Controlled burning may also stimulate growth and germination in some forests by removing competition from competing undergrowth vegetation.

Chemical Treatment

Chemicals used in forest management are generally pesticides (insecticides, herbicides, and fungicides) and fertilizers. Pesticides and fertilizers are occasionally introduced into forests to reduce mortality of desired tree species, improve forest production and favor particular plant species.

Many forest stands or sites never receive chemical treatment, and those that do typically do not require more than two or three applications during an entire tree rotation[36]. When a forester uses chemical treatments within a forest, it is important to monitor water contamination and run–off for environmental regulatory purposes.

Chemicals and fertilizers are typically applied from the air, but may be applied by ground force. Because of the risk of water contamination and the associated stringent environmental regulations, it is important to minimize use of chemicals and fertilizers. One method is to apply chemicals at precise locations by ground. There is potential opportunity to use unmanned aerial systems (UAS) to both identify locations requiring chemical treatment and to distribution chemicals, for example using a UAS platform such as the R–MAX[37] (See section 5.2.2).

Salvage Cutting and Sanitation Cutting

Salvage cutting, as the name implies, involves the early removal of injured or dead trees for the primary purpose of recovering usable material before it becomes worthless. Salvage cutting is common practice after fire or severe storm. Prior to salvage cutting, a forester may conduct a damage assessment survey to locate dead or injured trees and assess the financial impact.

Sanitation cutting similarly involves the removal of diseased trees, primarily to prevent the spread of disease through the forest and to recover usable material before it becomes worthless.

Harvest

The harvesting phase of a forest's life cycle is typically managed by the logging company, and thus most activities involved in this phase are considered out–of–scope.

One important activity during harvesting that may benefit from UAS or more general autonomous systems is the monitoring and prevention of soil erosion. Soil monitoring is only required in clear-cut forests, whereby all trees are harvested at the same time. Without the trees, the top mineral layer of the soil is prone to erosion, especially on steep hills and during heavy rain. It is not always possible to establish a new forest immediately after logging, and therefore, it is important to monitor the soil stability and condition to prevent landslide and protect the mineral layer. If the topsoil is eroded, new tree seedlings will not grow and the land may be rendered worthless. Figure 25 illustrates the impact of soil erosion when logging is not managed effectively.

Photo courtesy of wildmadagascar.org

Figure 25 – Erosion resulting from deforestation in Madagascar

Forest Planning and Maintenance

Throughout the life of a forest, a management company will undertake a number of activities that are not specific to any growth phase. These activities include developing the management plan, collecting forestry data to feed into the plan and general maintenance of roads and waterways.

Management Plan

A good forest management company will write and periodically revise a plan that states the manager's goals for the forest. Long–term (more than 10–year) goals are usually general. Short–term goals are more targeted, with specific practices and timetables. These include: timber stand improvement activities, stand thinning schedules, timber harvests, site preparation timetables and re–growth or re–planting (regeneration) methods and timings.

Maintenance

General forest maintenance activities involve the creation and maintenance of access roads, walking trails, fire breaks, environmental monitoring stations and campsites. Furthermore, the forest manager may be required to manage the health of river and water systems, commonly referred to as watershed management.

Forest Data Collection

Over the entire life of a commercial forest, it is important to periodically collect data on the state and health of a forest to feed into the forest management plan.

The Timber Cruise

Detailed forestry data is typically collected via a timber cruise, whereby a forester will walk, or 'cruise', the forest to measure trees and log data. During a timber cruise, measurements are collected at sample locations called plots or quadrants. Each of these individual plots is one observation in a series of observations called a sample. Using statistical sampling methods, observations made within each sample may be extrapolated to the rest of the forest, with varying levels of certainty given by the size and number of the sample plots. A typical fixed–size plot may be approximately 0.04 acres (160m^2) in size[38].

A detailed timber cruise is an important step prior to the sale of timber downstream to logging companies. Timber is typically sold before it is felled, and both the buyer and the seller must know the quantity and the quality of timber being sold. The cruise provides the essential data for determining stumpage rates, for establishing conditions of sale and for planning of the logging operations.

During a timber cruise it is important to determine the amount and quality of standing timber and the percentage growth or change in volume over time with respect to prior measurements. The most important parameters that are collected include:

Tree specific measurements:

- **Diameter at breast height (DBH)** – measurement of a tree's girth standardized at 1.3 meters (about 4.5 feet) above the ground.
- **Tree taper** – the degree to which a tree's stem or bole decreases in diameter as a function of height above ground.
- **Form factor** – the shape of the tree bole, as defined by how rapidly the tree's stem or bole decreases. It is largely related to the rate of taper – see Figure 26.
- **Volume** – total volume of a tree, which can be estimated from tree diameter, form factor, taper, and height measurements.
- **Age** – measurement of tree age can be done by taking a core sample and counting the number of annular rings. Tree age measurement is not required in many artificially regenerated forests where the age of stand is known.
- **Species** – tree species is determined through visual inspection by experts. Tree species determination is not required in in artificially regenerated forests where species is predetermined.

Site specific measurements:

- **Stocking** – a quantitative measure of the area occupied by trees relative to an optimum or desired level of density.
- **Stand density index** – a measure of the stocking of a stand of trees based on the number of trees per unit area and diameter at breast height of the average tree.

Most of the above forestry parameters that influence the value of a stand may be determined by measuring the diameter of sampled trees at various heights representative of the 10 per cent, 30 per cent, 50 per cent, 70 per cent, and 90 per cent of net height mark[39, 40].

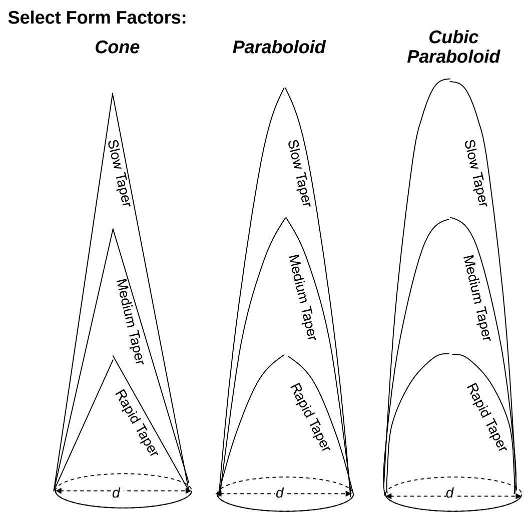


Figure 26– Illustration of Form Class and Taper[40]

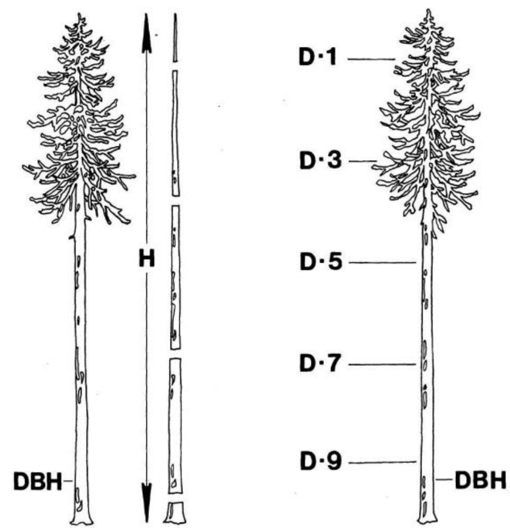


Figure 27 – Illustration of Diameter Quotients as a Means of Calculating Taper and Form[40]

Whilst standards and procedures for conducting a cruise are continuously evolving, the general methods and tools have not. Figure 28 depicts the most common tools used to conduct a standard cruise. Most of these tools have not changed significantly (with the exception of the GPS) over the past century, which indicates the potential for technology innovation.

Figure 28 – Common Tools for Conducting a Timber Cruise

Aerial Surveys

In addition to the timber cruise, a forest manager will frequently commission aerial surveys. Traditionally, aerial surveys involved taking high resolution photographs which could be used to determine forest borders and rough stocking over vast areas. Furthermore, aerial surveys can be used to detect disease and illegal land clearing. As will be discussed in section 4.3, recent innovations in the field of multispectral imaging and Light Detection and Ranging technologies have enabled forest managers to accurately measure parameters, such as tree height, via aerial survey. The traditional timber cruise, however, remains the only accurate means for determining diameter, taper and form.

Specialized Data Collection

In addition to the measurement of tree volume and stocking, a forest manager may collect data for any of the purposes illustrated in Figure 29. A forester may collect this information whilst conducting a standard timber cruise, or via aerial surveys.

Prior to commencing the product idea generation phase for this research it was important to determine the most frequently collected and valuable information for a forest manager. Whilst it is difficult to quantify the value of data for each of the categories listed below in Figure 29, qualitatively, the most valuable information comprises accurate volume and value data, and data pertaining to the early detection of insects and disease. This information relates directly to future cash flows of a forest management company.

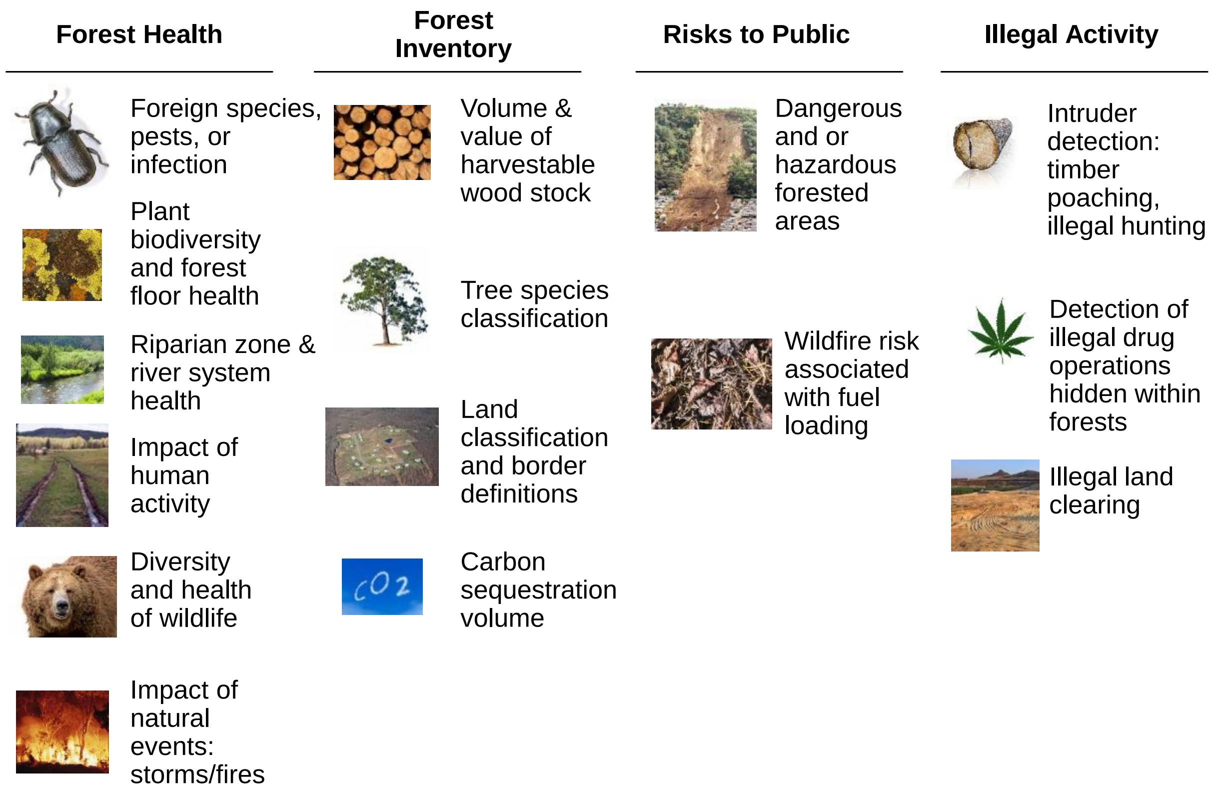


Figure 29 – Select Forestry Data Collection Activities

4.3 Active Research and Technology Trends in Forestry Management

This section describes active areas of research in the field of forest management. Space–based technologies and research pertaining to bioengineering are considered out–of–scope.

To evaluate the active areas of research and technology trends in forestry, four data sources were used:

- The evaluation of recent press releases relating to experiments or new technologies
- The evaluation of relevant research papers
- The evaluation of relevant patent applications
- The subjective opinions of subject matter experts obtained through interviews

Remote Sensing

Remote sensing refers to the use of aerial– or space–based imagery to create detailed maps of general forest characteristics to drive analytical models that produce useful and increasingly accurate forest statistics. Both private timberland owners and the Forest Inventory and Analysis National Program (FIA) have been using remotely sensed data obtained via satellite and aircraft for many years [38]. Research of remote sensing–based forest inventory and management approaches has been on–going since its inception in 1972, and remains an active area of research. Today, most research focuses on refining forest species classification techniques and developing lower–cost and more sophisticated laser based measurement methods (also referred to as Light Detection and Ranging).

Remote sensing technologies may be either airborne or space–based. In this technology review, we focus on airborne remote sensing at altitudes of less than 1km. This type of remote sensing may be deployed on commercial or civilian unmanned autonomous systems.

Remote sensing methods involve a variety of sensors and methods. Sensors can be broadly classified into three categories:

- Visible, Thermal, Multispectral, and Hyper–spectral Imaging
- Light Detection and Ranging
- Synthetic Aperture Radar

Visible, Thermal, Multispectral Imaging

Visible and multispectral imaging is the most common form of airborne remote sensing. A multispectral image is one that captures image data at specific frequencies across the electromagnetic spectrum. The wavelengths may be separated by filters or by the use of instruments that are sensitive to particular wavelengths, including light from frequencies beyond the visible range, such as infrared (see Figure 81 for an example of a multispectral camera). By capturing data beyond the visible spectrum, more information about a forest's condition may be inferred.

The amount of information that may be extracted from a multispectral image depends on the camera's four types of resolution:

- Spatial resolution: How many square meters are represented per pixel?
- Spectral resolution: How finely can a sensor distinguish between wavelengths and how large is the recorded frequency band?
- Radiometric resolution: How finely can a sensor distinguish differences in reflected or emitted energy intensity?
- Temporal resolution: How quickly can a measurement be repeated?

In general, high spatial resolution data can be used to determine forest inventory parameters including: assessing stocking levels, classifying vegetation types and spatially mapping tree parameters. High spectral resolution data can be used to ascertain forest condition in the form of nutrient deficiencies or pest and disease infestations. Radiometric resolution compliments both spatial and spectral resolution.

Most research in this field is associated with analyzing high spectral resolution data in order to distinguish between tree species[41] for accurate inventories, and to detect tree stress caused by pest or disease[42, 43]. Since tree species exhibit different cell structure and different concentrations of chlorophyll, cellulose, and natural water content, each tree species has a unique spectral signature referred to as vegetation spectra. The vegetation spectra for a variety of common species found in the United States is illustrated in Figure 30. Often the vegetation spectra are used to calculate various statistics that describe the state or health of a forest. These statistics are referred to as vegetation indices, the most common is the Leaf Area Index[44].

Whilst research into tree species classification using multispectral imaging is on–going, classification is still crude, due to challenges in detecting subtle differences between a species spectra and the natural variation in water and chlorophyll content throughout the year. Multispectral imaging, however, has demonstrated great success in detecting disease and other stresses, due to a detectable change in the vegetation spectra caused by reduced leaf water content.

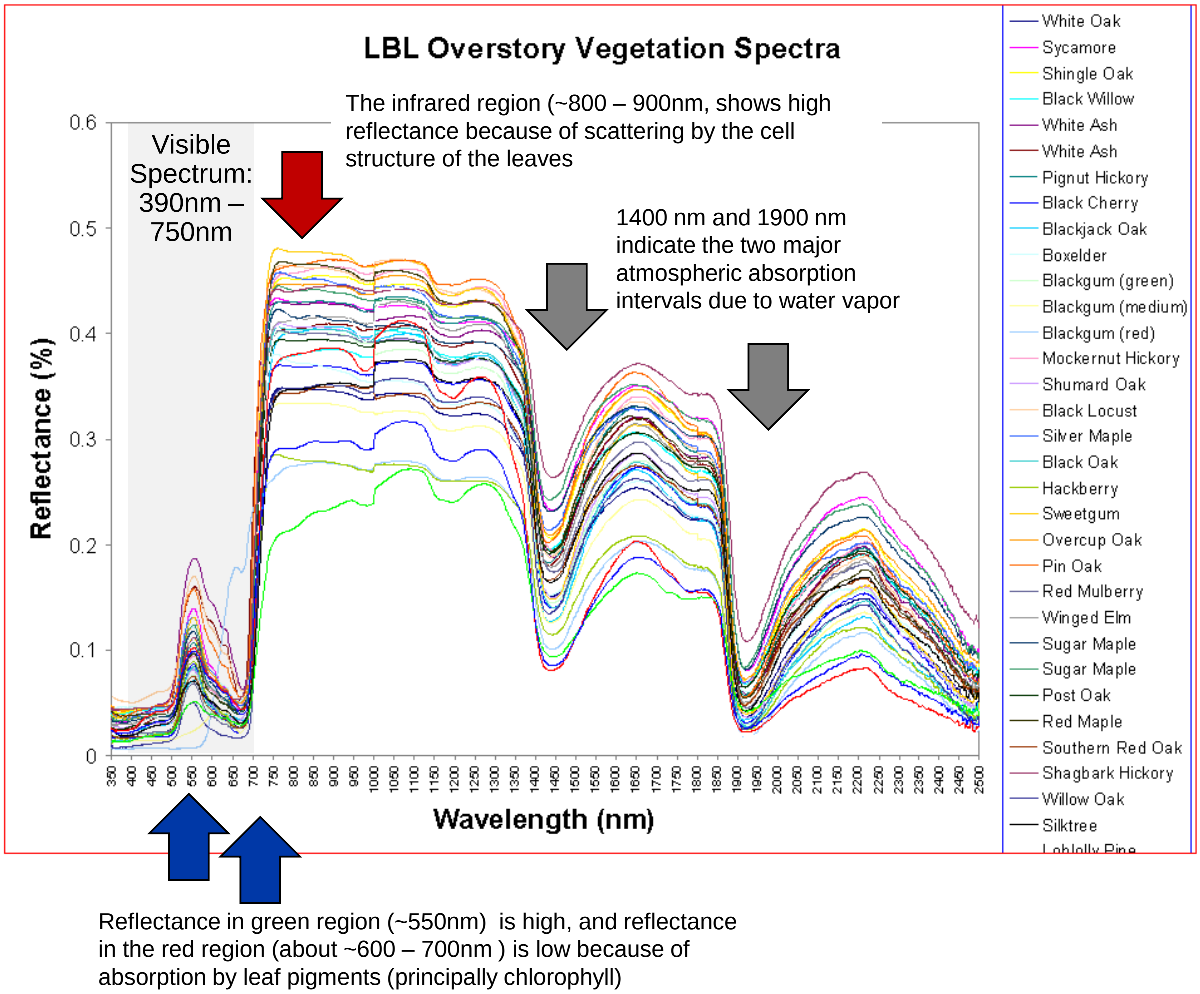


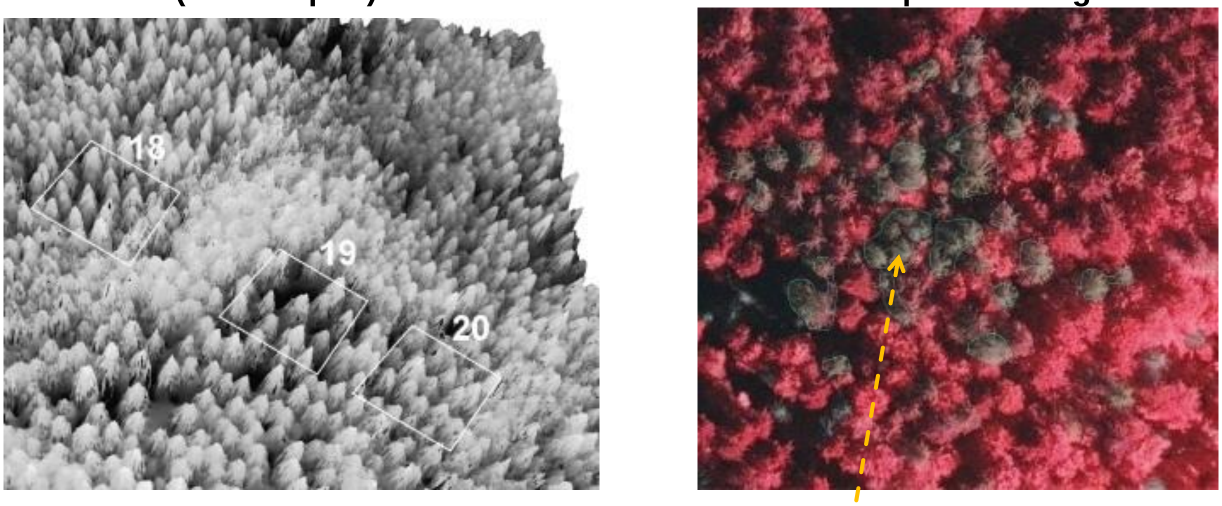
Figure 30 – Vegetation Spectra of Common Tree Species found in North America[45]

Aerial LiDAR (Light Detection and Ranging)

Remotely acquired Light Detection and Ranging (LiDAR) data is becoming increasingly important to public and private forest managers[46]. A light detection and ranging apparatus estimates relative distance to a target by measuring the delay in the return signal of a light pulse. When mounted on an aircraft, a LiDAR apparatus can measure the height of individual trees in the forest by comparing the distance to the ground and the distance to the top of individual trees. Furthermore, high resolution LiDAR data can be used to generate a 3–dimensional model of the forest canopy, which can be used to accurately measure tree count, forest density and canopy structure. Such information is difficult to measure using traditional digital imagery only. Much research is on–going into lower–cost and more accurate LiDAR apparatus, methods for processing LiDAR data, and integrating LiDAR data with other remotely sensed information such as multispectral imagery and historic data sets[46–48].

High resolution LiDAR data (surface plot)

Artificial color representation of multispectral image



LiDAR data can be used to distinguish between individual trees for a more accurate tree count, and can be used to accurately measure tree height.

Healthy trees appear red; stressed trees appear grey due a decrease in reflectance in the near infra red band as a result of chlorophyll loss.

Figure 31 – Examples of high density LiDAR data and multispectral data

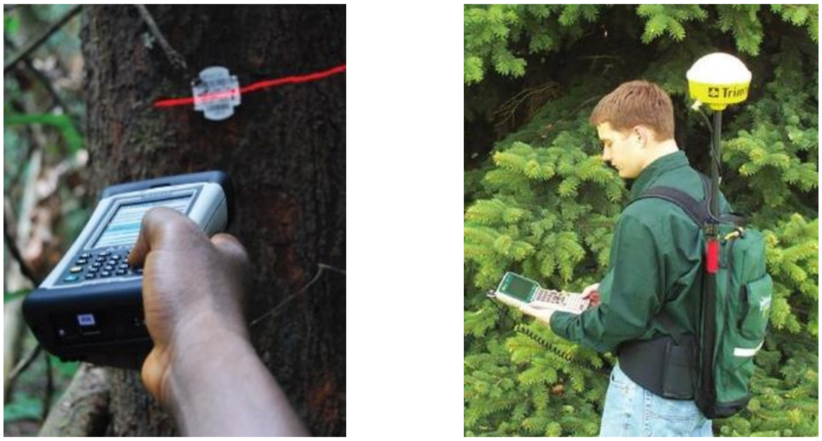
Synthetic Aperture Radar (Active) and Microwave Radiometer (Passive)

Radar based remote sensing methods complement the more common multispectral and LiDAR based methods, because radar is sensitive to different forest parameters, namely forest structure and the moisture content of the canopy and underlying soil. New techniques using radar have demonstrated the potential for species discrimination[49]. In 2008, the Boeing ScanEagle was demonstrated with a miniature 2lb Synthetic Aperture Radar instrument[50] demonstrating the potential to utilize small unmanned aerial systems for radar based remote sensing tasks.

The Forest Cruise

Terrestrial Recorders

Even with the advent of airborne and space–based remote sensing technologies, a significant portion of forestry information is gathered through terrestrial forest surveys. Important information, such as diameter and taper measurements, cannot be accurately measured by air. Whilst most survey methods have not changed significantly, there has been some research and advances in the way data is recorded. For example, a forest worker may now enter data directly into a hand held computer integrated with a GPS system. The GPS can identify the exact location from which the data was generated, using the Geographic Information System. Other advanced methods include the use of barcode tags and scanners for more efficient data entry on trees that require repeated surveying (Figure 32).



Scanning Barcodes in Forests Enhances Forest Management

Handheld Computer with GPS Technology to Integrate with GIS

Figure 32 – Forest Workers with Modern Data Recorders

Terrestrial Laser Scanners

A recent area of research interest is the use of terrestrial LiDAR scanners or (T–LiDAR) for measuring forest parameters. Terrestrial LiDAR, similar to its airborne counterpart, uses laser to accurately measure the distance to a point on a nearby objects. When enough points are measured, a point cloud is generated that can be used as a 3–dimensional digital representation of an object or local environment. Terrestrial LiDAR is traditionally used in industries such as mining and construction.

Because industrial terrestrial LiDAR scanners are capable of making millions of measurements in a short time frame, they can be used to generate an accurate representation of a forest environment, such as the representation in Figure 33. Much research is associated with the development of point cloud processing methods and software to effectively extract important forest measurements from the point cloud data[51, 52]. For example, *AutoStem Forest*^{TM}[53]is a software package developed by a start–up company Tree Metrics to extract important tree measurements, such as stem volume and taper. This information can be used in conjunction with optimal bucking software for detailed cutting simulations, to assess different harvesting options and to calculate yields based on different sawmill requirements [54–56]. *VALMAX* by Glen Murphy[56] is one such software package that can be used with *AutoStem Forest*^{TM} to accurately estimate the dollar value of a timber stand before it is harvested.

Based on conversations with forestry companies in the US, the use of terrestrial LiDAR is still cost prohibitive for most forest managers. Whilst the price of the equipment has reduced significantly, the method still requires a human operator to control the scanner. Latest generation terrestrial scanners are relatively cheap, costing approximately $40,000 as of 2012, and are capable of scanning 360 degrees out to a range of approximately 30m in around 2–8 minutes.

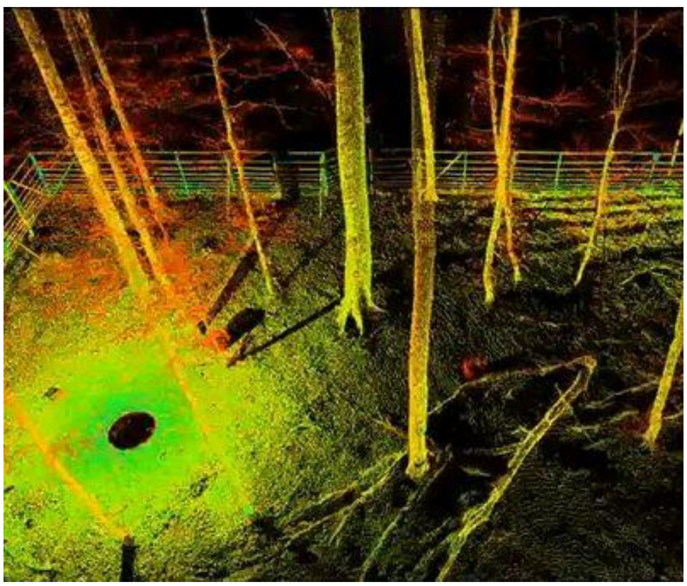


Figure 33 – Artificially colored 3D point cloud of a German beech forest

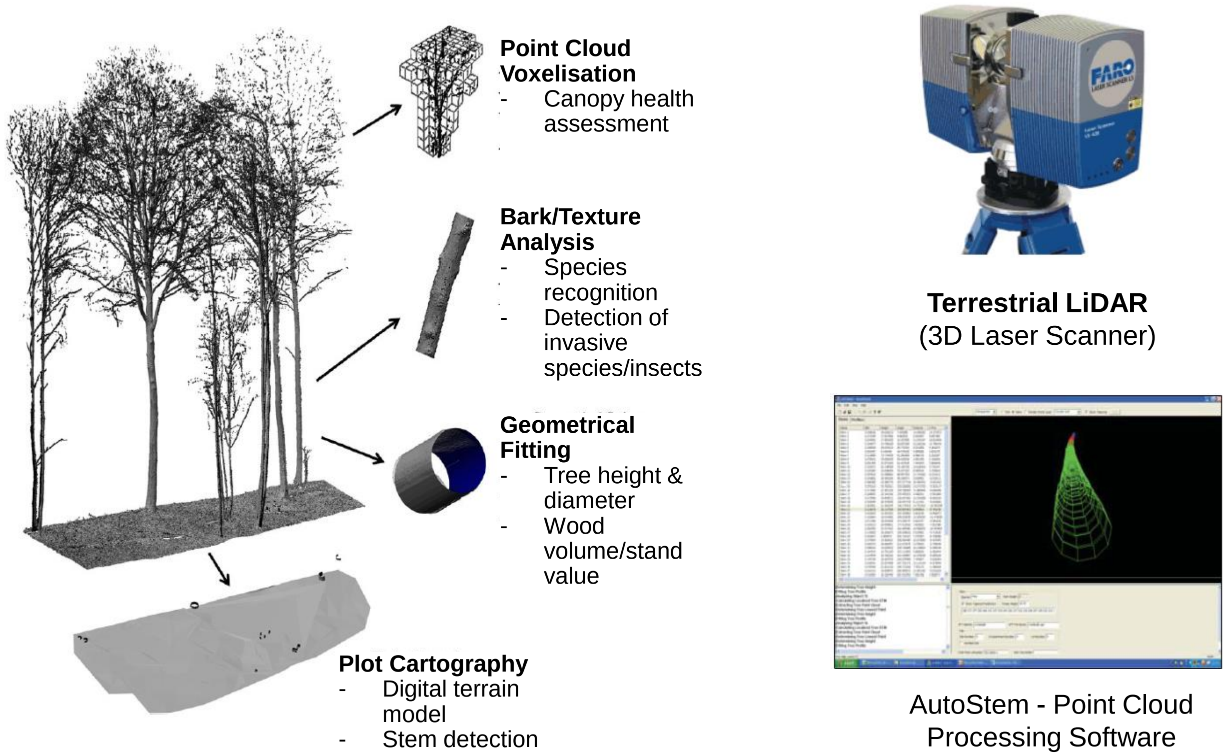


Figure 34 – Terrestrial LiDAR Scanner and Point Cloud Processing Software

Integrated Management Models

Integrated forest resource management tools are software systems designed to integrate the various aspects of forestry management throughout the entire life of a plantation. These systems may include functionality for machinery operation, machinery maintenance and management, record management, financial management, forest growth modeling and analysis of remote sensing and cruise data.

Integrated resource management tools may also provide statistical analysis tools to manage the important related task of data interpolation between field samples. Forest monitoring involves sampling of small plots (called conditions) and interpolating between sites (spatial interpolation) and between timeframes (temporal interpolation). This task requires a statistical framework to interpolate between surveys and characterize error[57].

No single software package or system is capable of the all the aforementioned resource management tasks. Research is on–going into how to better integrate various data management systems and how to better fuse data from multiple sources for better decision support[58].

The Geographic Information System (GIS)

The geographic information system, also known as GIS, is one such tool that integrates data obtained by remote sensing technologies, terrestrial surveys and management plans. GIS systems store different information sources into information layers as illustrated in Figure 35. Any data that is geo–referenced with GPS coordinates may be integrated into the GIS data model. GIS technologies enable a forest manager to independently develop management strategies for each sector of a forest and evaluate changes in the forest over time.

The GIS management system has become such an important tool in forestry that it is now an active area of research. ESRI, an industry leader in GIS technologies, has a dedicated forestry research laboratory and hosts a dedicated research conference, 'Forestry GIS Conference'[59, 60].

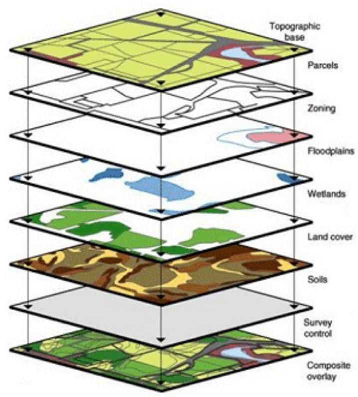


Figure 35 – Illustrative Geographic Information System Data Model

Value management and planning software may integrate into GIS systems to assist with specific planning and decision tasks across the life of a commercial stand. These software packages are not flexible analysis tools, but rather specific packages designed to streamline regular analysis tasks. The following software packages are designed for this purpose, and are built upon the ESRI GIS technology discussed above:

- Cengea Forest by Cengea Solutions
- Forester by ESRI UK.

Forest Growth Models

A forest growth model is a computer program that estimates forest yield by integrating all factors known to affect forest growth. For example, research has indicated that normal growth is strongly influenced by: (1) the size or age of the tree, (2) the quality of the site or environment, (3) the degree to which the tree is affected by competition from other trees, and (4) the effects of disease or insects. These variables are converted to mathematical equations in a growth model to predict future growth performance.

Using inputs like rainfall, temperature and soil salinity, these models can reduce the need for regular site visits by estimating plantation performance using empirical models. Furthermore, growth models may be used to evaluate different management strategies to optimize growth and yield. CABALA by CSIRO Australia[61] is one such model designed for decision support analysis.

Whilst research is on–going on a number of fronts, greater integration is required across the various forest management systems and tasks. In particular, better integration and fusion of data sources is required. Figure 36 is a basic framework to consider the various elements of an integrated Forestry Management System.

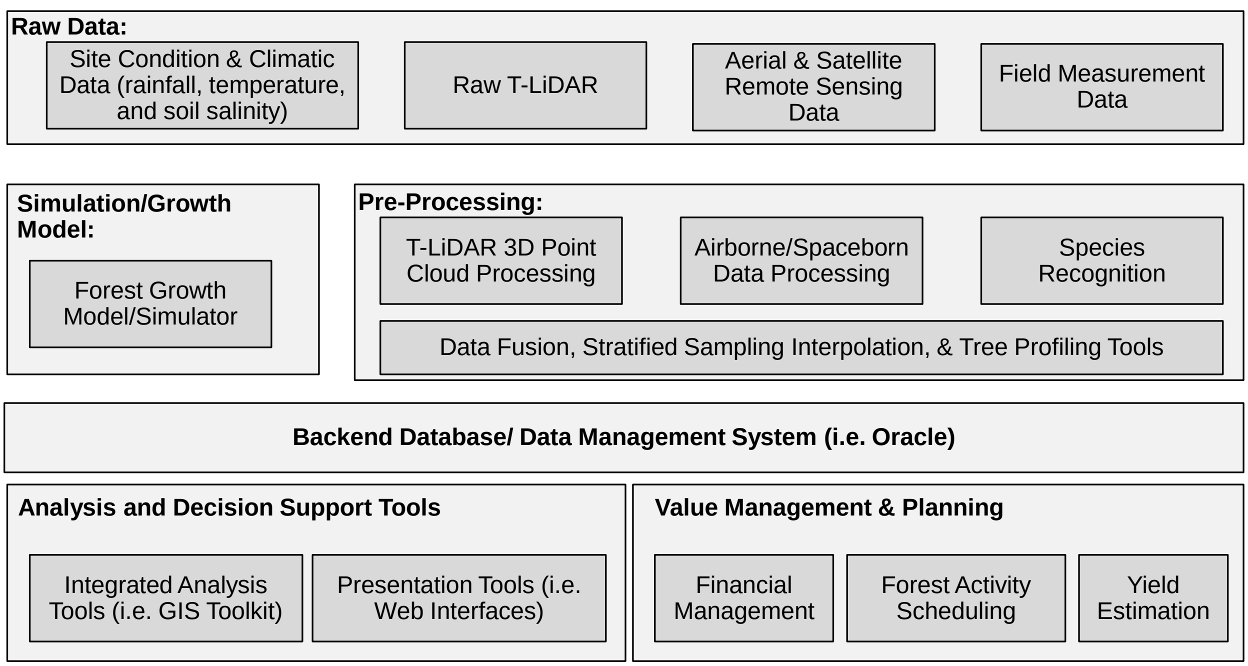
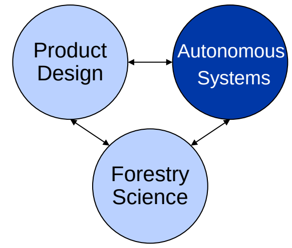


Figure 36 – Framework for Integrated Forest Management System

5 Industry Review – Commercial and Civilian Autonomous Systems Market



This chapter describes the emerging commercial and civilian autonomous systems market, including a discussion of opportunities, challenges and technology trends. In Section 5.2.1, we review emerging technologies as they relate to the industry as a whole. In Section 5.2.2, we present a number of case studies of experimental technologies directly related to the field of forestry management. The reader that is familiar with autonomous systems research and vernacular may find this chapter unnecessary to read.

Whilst autonomous systems may refer to any autonomous or semi–autonomous system involving one or more fixed or mobile sensor platforms, much of this chapter focuses on small and micro Unmanned Aerial Systems (UAS), given their importance to the proposed systems of Chapter 7.

5.1 Industry Structure and Market Trends

It is important to first define the difference between the commercial and civilian autonomous systems markets. The civilian segment comprises system purchases by non–Department of Defence federal agencies such as the Department of Homeland Securities (DHS) or the US Forest Service. This segment also includes state and local entities, such as regional departments of public safety, municipal police departments and fire departments.

The commercial market segment includes system purchases by non–government organizations. Examples of commercial end users include petroleum companies, real–estate agencies, broadcasting companies and commercial forestry companies.

Most industry growth to date has occurred in the sale of Miniature–class Unmanned Aerial Systems/Vehicles or MUAV. This segment can be further broken into miniature vertical take–off and landing (VTOL) platforms and miniature fixed wing platforms.

Platforms

Figure 37 depicts a selection of unmanned aerial system (UAS) platforms available to the civil and commercial sectors. These platforms range in price and capability. For example, the AR Drone by Parrot is targeted at the hobby market, and retails for less than $300. It is not capable of carrying any additional payload. The more advanced systems are capable of carrying payloads of up to 1.2 kg for over an hour, and are capable of advanced way point navigation for autonomous flight beyond the line of sight of the operator. Many platforms are marketed towards the first responder industry, such as police forces or fire departments. By the end of this century, many more companies and platforms are expected to emerge as more and more venture capitalists invest. Note that this thesis does not endorse any particular vehicle platform.

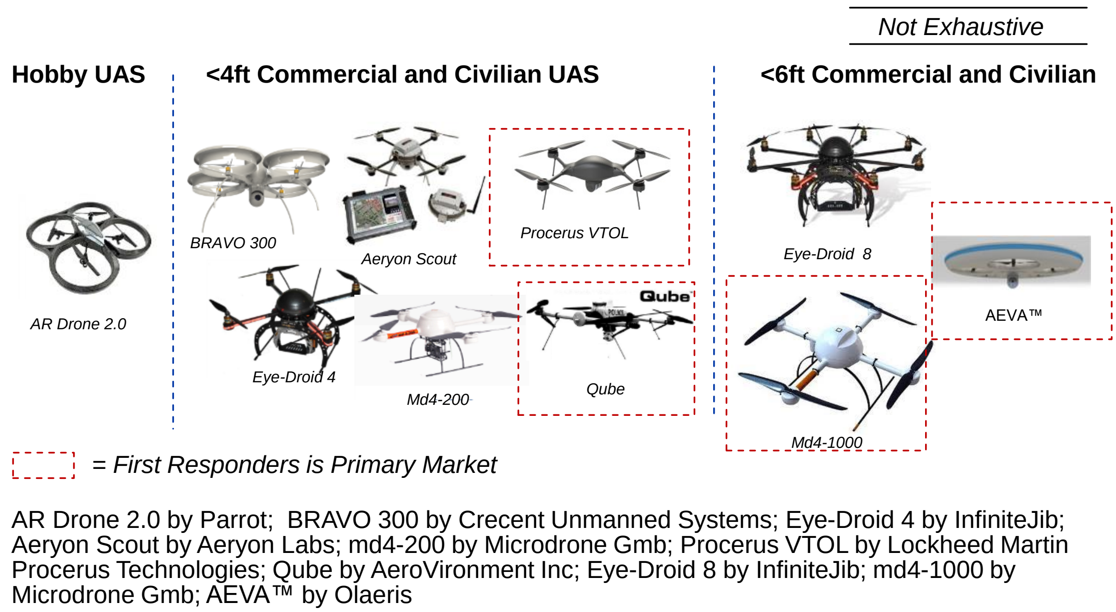


Figure 37 – Select Civilian and Commercial Micro VTOL class UAS

Figure 38 depicts a selection of current micro–class fixed wing platforms. Many of these platforms are designed as low cost aerial mapping platforms. Some are targeted towards the precision agriculture industry. The long endurance category, such as the Super Bat by MLB Company and Scan Eagle by Boeing, are predominantly limited to military applications, due to their greater mission capability.

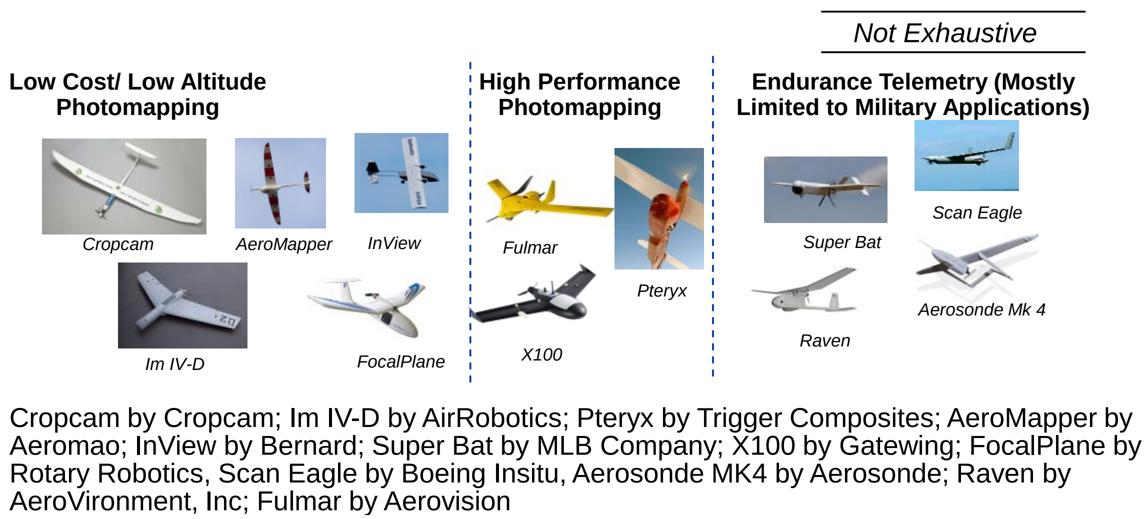


Figure 38 – Select Civilian, Commercial, and Military Micro Fixed Wing UAS

Market Segments

A number of industries have explored the use of Unmanned Aerial Systems and Autonomous Systems. Figure 39 provides a list of current or proposed applications based on available literature[5, 62].

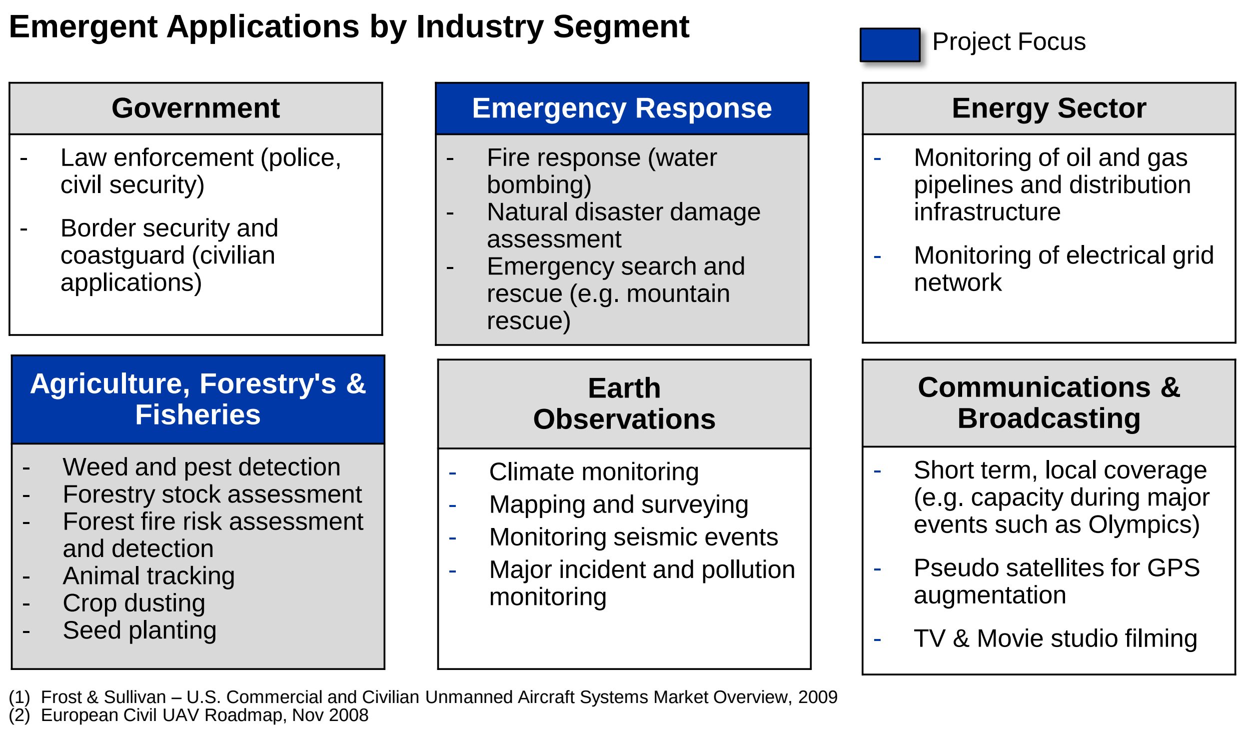


Figure 39 – Emergent Applications for Autonomous Systems by Industry

Border surveillance, disaster response and public safety are the most notable civilian applications for unmanned aerial systems to date. For example, recent natural disasters have drawn attention to the benefits that UAS can provide to first responders, particularly for search–and–rescue efforts. Utilizing unmanned aircraft following natural disasters, however, has proven a challenge due to airspace regulations, as will be discussed in Section 5.3.

The fastest–growing industry segment is the first responder industry, including police and fire departments. Recent regulatory changes are making it easier for first responders to acquire and deploy micro UAS[63].

Market Size

Despite strong interest by a number of industries, revenue generation for commercial and civilian UAS in the United States is expected to remain slow in the short term, in part due to airspace regulation. In 2010, the total US market was estimated at only $33 million[4]. By 2015, new regulations are expected, and the industry rate of growth is predicted to accelerate – see Figure 40. Many industry experts predict that by

2025 the technology will begin to mature, and widespread adoption will begin. Many industry experts predict that, in the long term, the commercial and civilian market for UAS will outpace the military market and will enter into the billions of dollars[5].

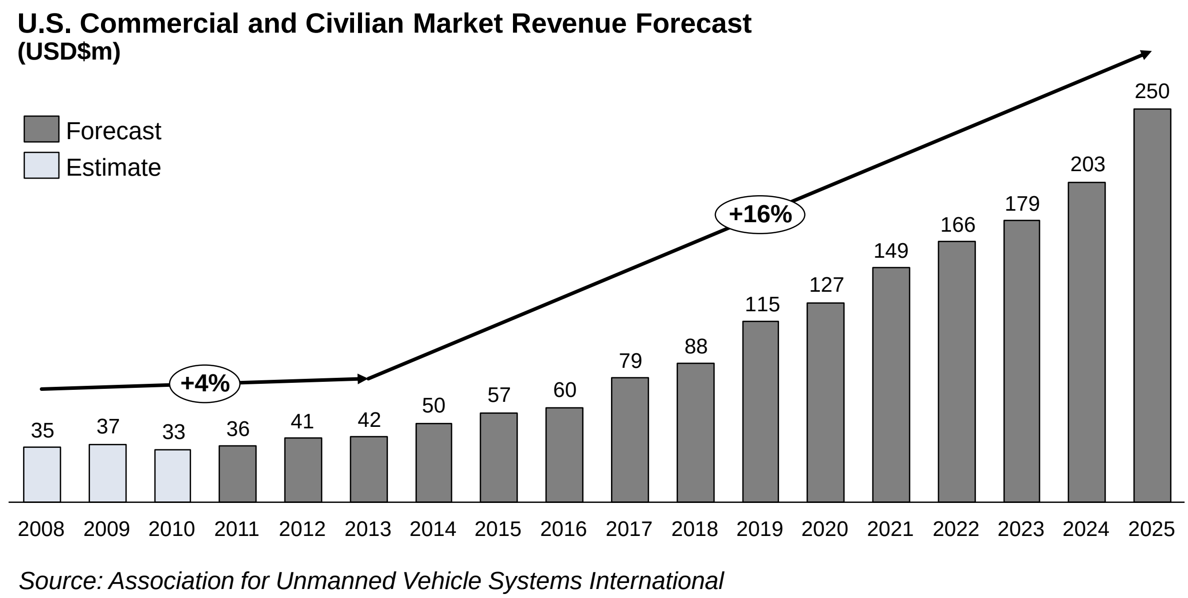


Figure 40 – U.S. Commercial and Civilian UAS Market Size Forecast

Business Model Innovations

To help kick start the UAS industry, new entrants such as Olaeris are innovating not only with their technology, but also in their business models. To win over the United States first responders market, Olaeris offered $15 million to any emergency response agency, including state police and fire department, ‘to prove that their unmanned aerial system will reduce the cost of providing emergency services by at least one million dollars per year, per city’[64]. The Olaeris proposition is that once installed, when a 911 police or fire emergency is received, the Olaeris platform can arrive anywhere in the service area within 90 seconds. The average national response time is 8.5 minutes. This will allow responders to assess the situation faster and adjust their response based on what is happening at the location.

The Olaeris business proposition suggests that future winners in the autonomous system market may need to define their value proposition and target markets, focusing efforts towards specific market needs, rather than betting on generalist platforms. Winners may need to innovate both in technology and business models. The success of any new forestry management technology will be dependent on a clearly defined value proposition to commercial forestry companies.

5.2 Active Research and Technology Trends

The field of autonomous systems has undergone significant technological advancement over the last decade, including advances in the performance of platforms, sensors, control systems and algorithms. This section briefly reviews active areas of research.

5.2.1 Active Research Themes

Swarm Technologies

Vehicle swarms have the potential to efficiently carry out many challenging forestry missions. Vehicle swarms comprise multiple, interacting and mobile platforms (agents), that collaborate in an autonomous manner as a means to means to reduce overall mission completion costs, while expanding mission capabilities and improving mission assurance.

Vehicle swarm technologies are still in their infancy, yet research progress is rapid. Advances in systems health management technologies now enable swarms to monitor their own condition and capabilities, thus creating the opportunity for new levels of adaptive control, real–time reconfiguration and mission contingency management. Furthermore, advances in multi–agent task allocation and mission management systems have demonstrated the ability to account for vehicle– and system–level health–related issues, to ensure that these systems are reliable and cost effective to operate[65].

Dedicated facilities for low cost rapid prototyping of complex, coupled autonomous systems, such as the Boeing and MIT laboratories of Figure 41, play an important role in the development and testing of practical autonomous systems technologies[65, 66].

Rapid Prototyping Vehicle Swarm Lab, Boeing – Courtesy Dr. John Vian, Boeing

10 UAV quadrotors flying autonomously. The team flight is initiated by a single operator. (March 2007) - Courtesy Professor. Jonathan How, MIT

Figure 41 – Demonstration of Swarm Technologies

Advanced Navigation and Obstacle Avoidance Methods

Advanced navigation and obstacle avoidance algorithms and methods now enable small unmanned aerial systems (UAS) to navigate autonomously through complex environments. In the near future, it may be possible for a small UAS to navigate autonomously and reliably below the forest canopy to collect forestry data.

For example, using a machine learning technique called Imitation Learning, a team at Carnegie Mellon recently developed software for a small, commercially available off–the–shelf AR.drone to autonomously navigate through an unstructured, natural forest environment[67]. In December 2012, the team flew the AR.drone through a forest for over 3.4km at a constant velocity of 1.5m/s during experimental runs. Furthermore, the autopilot used only a single cheap camera to perceive the environment.

Since the AR.drone and other Micro UAV have a very limited payload capacity, autonomous obstacle avoidance poses a challenge, given that only very small sensors may be used. The autopilot was trained using a set of set of human pilot demonstrations.

Figure 42 – UAS Navigation through Learned Monocular Reactive Control

Navigation in GPS–Denied Environments

Most autonomous navigation systems utilize the Global Positioning System (GPS) for estimates of position and velocity. Many environments, such as inside a building or below a dense forest canopy, have poor GPS signal, and navigation algorithms must rely on more sophisticated methods for state estimation. The problem of navigation within GPS–denied environments is by no means solved; however, progress has been incredibly rapid.

One research group that has made significant advances in the field of GPS–denied navigation is MIT's Robust Robotics Group. The group has developed and successfully demonstrated algorithms for calculating a fixed winged MUAV's trajectory[68] and for determining its 'state'[69]: its location, physical orientation, velocity and acceleration (See Figure 44).

Figure 43 illustrates a micro UAV developed at MIT that won the 2009 International Aerial Robotics Competition (IARC), hosted by the Association of Unmanned Vehicle Systems International (AUVSI) [70]. The micro UAV successfully navigated through the 3–dimensional maze, as depicted in the figure, without the use of GPS. Figure 44 depicts a small, fixed wing system developed by researchers at MIT that has demonstrated autonomous flight in complex GPS–denied environments.

These methods and algorithms will be important to the development of any mobile autonomous system designed to navigate below the forest canopy.

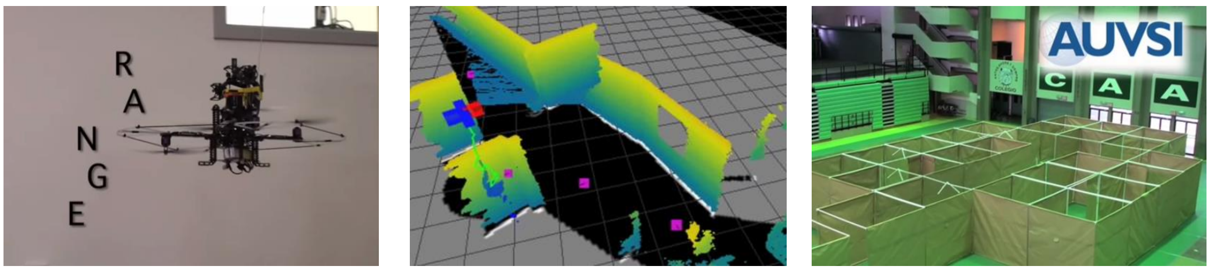
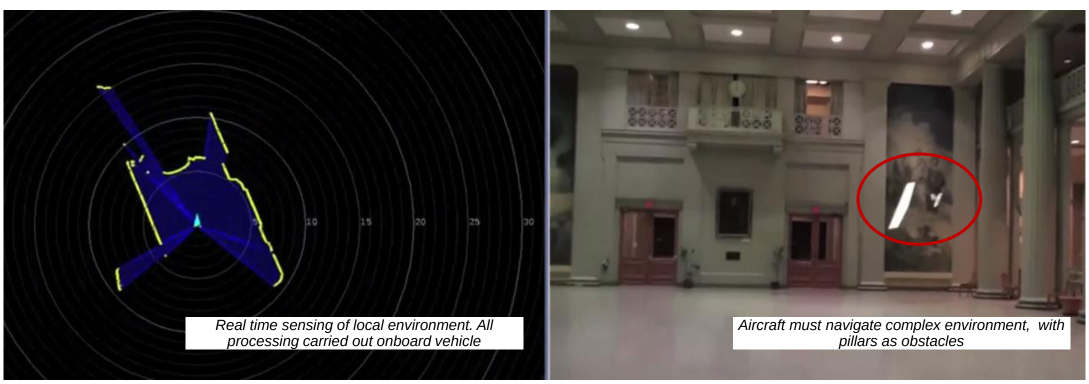


Photo of RANGE MAV developed by the team under Nick Roy at CSAIL MIT.

3D Map generated by MAV

2010 ICRA Competition Maze

Figure 43 – Robust Autonomous Navigation of MUAV in GPS–Denied Environments



Fixed Wing UAV capable of autonomous flight in GPS denied environments. Courtesy Professor Nick Roy and Jonathan How of CSAIL MIT.

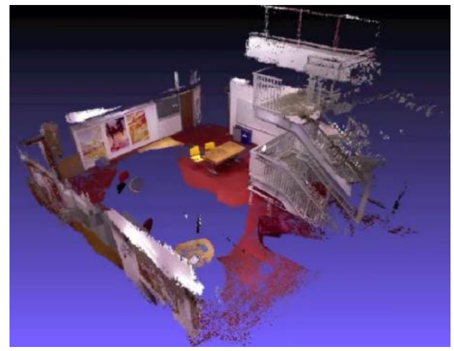
Figure 44 – Autonomous Navigation of Fixed Wing UAV in GPS–Denied Environment

3D Mapping and Measurement

A strongly related problem to that of navigation in GPS–denied environments is that of mapping and measurement using small and lightweight sensors. A number of research teams are tackling this challenge using a variety of approaches, including the use of small laser range finders, stereoscopic cameras, and, more generally, time of flight cameras[71, 72].

The Microsoft Kinect is one example of a time of flight camera and has attracted much recent attention due to its low cost. The Kinect’s depth sensor consists of an infrared laser projector combined with a monochrome CMOS sensor that captures 3–dimensional data up to a ranging limit of approximately 3.5m. In Figure 45, a micro UAV (MAV) is used to map its local environment using the Kinect, generating a relatively detailed point cloud and texture map.

Berkeley quadrotor that navigates with Kinect Sensor only

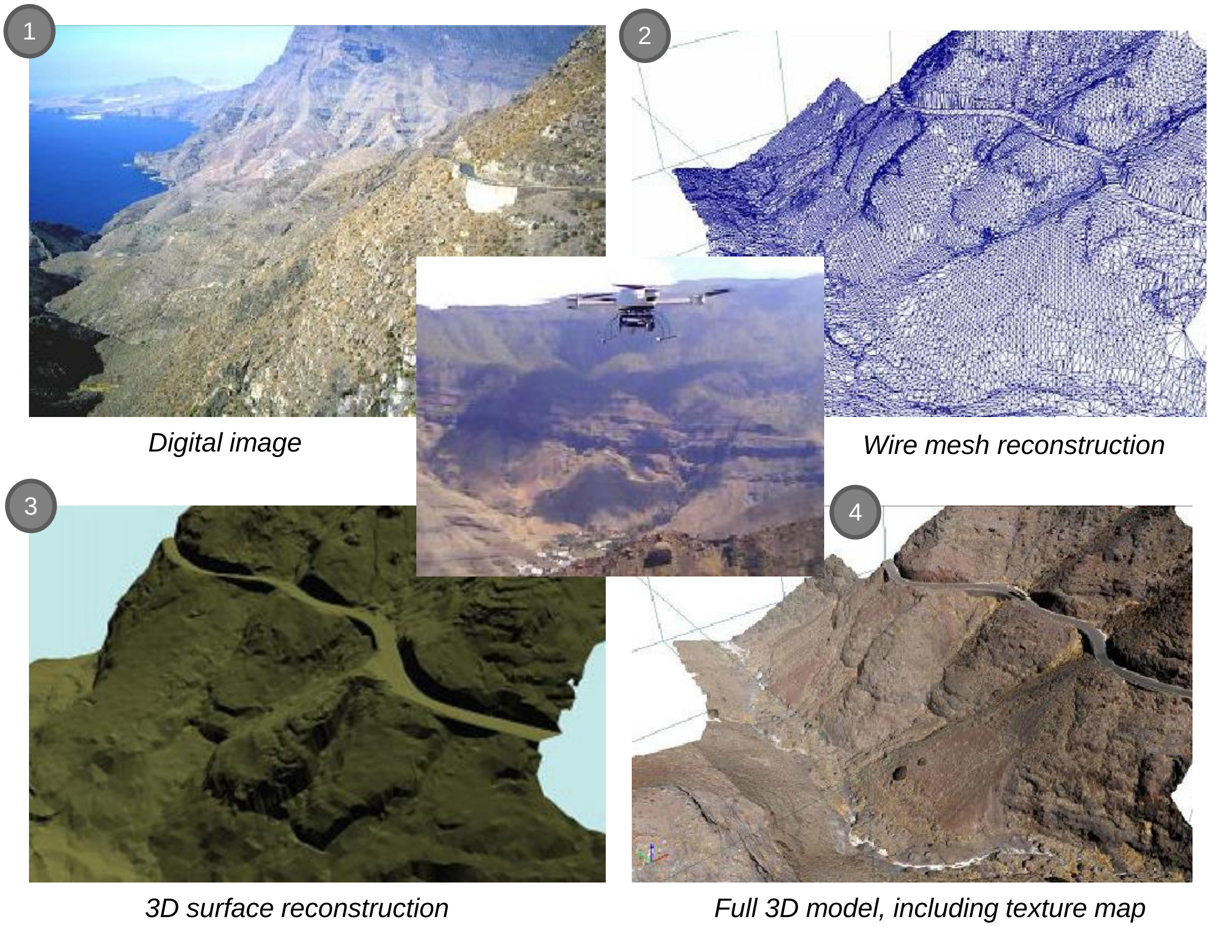


3D reconstruction of local environment using Kinect Sensor

Figure 45 – Mapping and Measurement using Microsoft Kinect

UAS manufactures have also demonstrated the ability to capture detailed aerial 3–dimensional data using a single standard digital camera[73]. For example, the civilian and commercial UAS company, Microdrones GmbH, recently introduced a commercial 3–dimensional aerial mapping product using its MUAV Md4–1000 platform using an off–the–shelf Sony Nex7 camera. The system captures numerous digital photos of the terrain from multiple perspectives, which are then used to reconstruct a 3–dimensional terrain model during post process. Using a well–known technique referred to as photogrammetry (or stereophotogrammetry), common points on each image are identified, and depth information is then estimated through triangulation. Given the Md4–1000 can operate for up to 88 minutes, relatively large areas can be mapped during any given flight. This technology could, in theory, be used as an alternative to LiDAR to map a forest canopy.

Figure 46 demonstrates the process, illustrating a 3–dimensional digital terrain map generated of a road on western coast of Gran Canaria Island[74].



Images Courtesy of: microdrones GmbH and INGECOR Geomática SL

Figure 46 – 3D Terrain Mapping with a Single Digital Camera

Power Management Systems

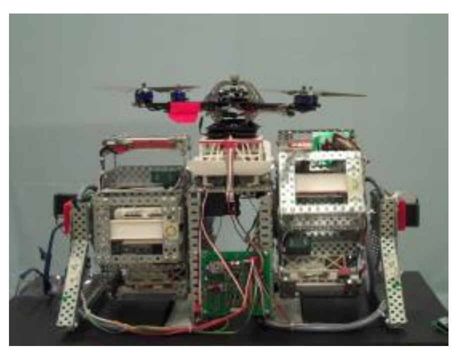


Image courtesy J. How, MIT

Figure 47 - Autonomous Battery Swap and Recharge Station

Flight time of electric UAS is limited by battery technology. To enable greater flight times and persistent autonomous operation, researchers have developed a number of new technologies. For example, researchers at MIT have recently developed a battery charging station[75]. Autonomous UAS systems may land briefly on the station and change batteries without powering off.

Another approach to the power challenge is to use wireless power transmission technologies. In 2012, Lockheed Martin, in collaboration with LaserMotive, demonstrated how a laser situated on the ground could act as an energy source for an operational UAS in flight, to recharge the on–board power cell. The research team extended the flight time of a modified Lockheed Martin Stalker UAS to more than 48 hours using the technology[76].

Whilst it is unlikely that power beaming will be made available to commercial and civilian autonomous systems due to regulation, autonomous battery charges and other ingenious power management technologies may enable a myriad of new civilian autonomous technology applications.

5.2.2 Case Studies of Autonomous Systems in Forestry and Agriculture

Case 1 – Real time fire detection and tracking using remote sensors

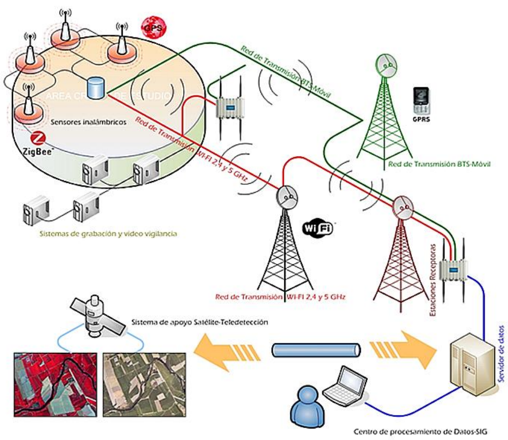
Research into wireless sensor networks, a category of autonomous systems, has led to the development of sensor networks designed to detect and track fires in real time[77, 78].

In 2010, Spanish research institute, DIMAP–FactorLink, developed and tested an integrated forest fire detection system using low cost, off–the–shelf Waspmote wireless sensors. The proof of concept system was tested on approximately 210 hectares of forest in Northern Spain[79].

The proof of concept incorporated a wireless mesh network of 90 sensors, strategically placed throughout the forest. Each sensor measured and relayed four parameters every five minutes: temperature, relative humidity, carbon monoxide (CO) and carbon dioxide (CO2). Furthermore, each sensor incorporated rechargeable batteries and micro solar panels for persistent operation and complete autonomy.

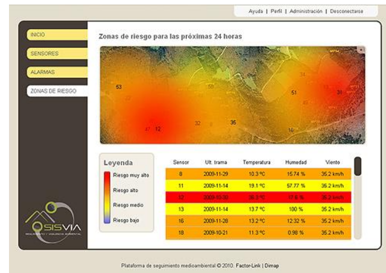
As illustrated in Figure 48, the system design comprised three integrated systems, including the wireless sensor network, the communications network and the processing center. At the recipient processing center, the system was used effectively as an early detection system for new fire outbreaks. Furthermore, the system was able to track the propagation of fires in real time, enabling the development of effective firefighting strategies.

DIMAP System Architecture



Libelium Waspmot Gas Sensor

Real-Time System Interface



(1) Detecting Forest FireWaspmote, Libeliums using Wireless Sensor Networks with Waspmote, Libelium press release 2010

Figure 48 – Forest Fire Early Detection and Monitoring System Utilizing a Mesh Network

Case 2 – Bio–energy harvesting for persistent remote monitoring

Founded in 2008 by a team from MIT, Voltree Power has developed and commercialized the first bio–energy harvesting sensor platform[80]. Bio–energy is a form of energy harvesting that converts living plant metabolic energy from a tree to useable electricity, providing a battery replacement alternative for ultra–low power sensors. The energy system is weather resistant, leaves no heat signature and is entirely environmentally benign. Furthermore, once installed, a Voltree's bioenergy harvesting system is expected to operate for 15–20 years without maintenance, providing a distinct advantage over other energy harvesting technologies for remote forestry applications[80, 81].

The sensor platform has been deployed by a number of environmental agencies, such as the US Forest Service and the Bureau of Land Management. The bio–energy harvesting platform has recently been deployed to detect the Asian Longhorn Beetle, a pest introduced to North America that has caused widespread damage to hardwoods in the USA and Canada. The Voltree sensor platform may be configured into a sensor mesh network for numerous applications. Other ambient energy harvesting technologies that may be used in low light conditions below the canopy include ambient solar[82] and energy harvesting from tree movement driven by low levels of wind[83].

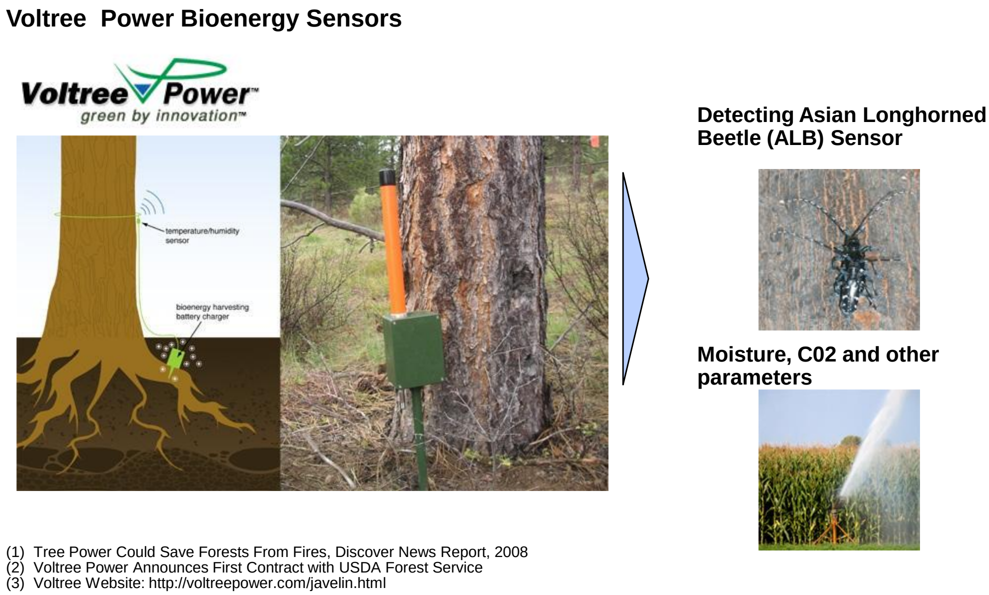


Figure 49 – Voltree Bio–Energy Platform

Case 3 – Yamaha RMAX for autonomous crop spraying

The Yamaha RMAX is one of the first and most successful commercial unmanned autonomous systems [37]. The RMAX is a small autonomous helicopter, capable of carrying a payload of up to 30kg. The first–generation platform was originally designated in the late–1980s for the needs of the Japanese agriculture industry. The platform was so successful in Japan for agricultural spraying that by 2005, more land was sprayed using the RMAX than by any other method (Figure 50). RMAX is also popular for aerial photography and monitoring applications, and by the movie industry for overhead filming. RMAX is designed to operate as a Visual Line of Sight (VLOS)–class UAS, however, it is fully equipped with a sophisticated autopilot and may operate out of sight by means of a GPS autonomous flight system. The system is sold only in countries where commercial UAS are legal, with some adoption in Australia and South Korea. The RMAX can only be purchased as an integrated system, comprising a ground station, control computers and monitors, two airframes and four camera systems. The system retails for approximately $1,000,000.

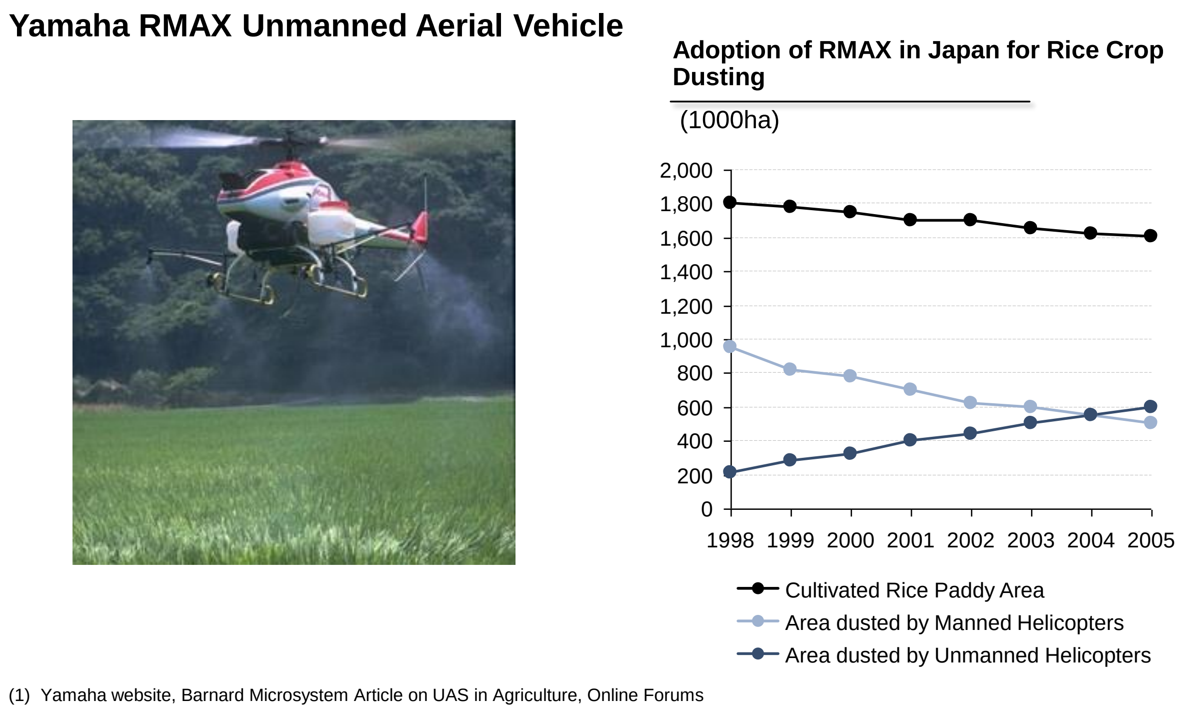


Figure 50 – Yamaha RMAX Small VTOL UAS

Case 4 – Monitoring animal populations

A growing body of research is dedicated to the use of remote sensing methods to monitor wildlife populations. There are three areas of research:

Animal tracking with Autonomous Recording Units

The field of bioacoustics is focused on the design and application of digital recording equipment, computer software and algorithms, to study animal communication and to monitor the health of wildlife populations. These systems are referred to as Autonomous Recording Units (ARU). Various generations of ARU have been developed since 1995, and have been deployed in marine environments to monitor whale populations and other marine species, and more recently in terrestrial environments to monitor bird populations and other animals.

Among the crucial features of an ARU are its small size and its low power consumption. These features enable an ARU to sit alone for weeks or even months, powered by D–cells or 12–volt batteries. Up to 80 gigabytes of digital recordings can be collected by a single unit. Sophisticated software now enables scientists to recognize a particular bird species from the recorded bird song, thus enabling a count of population[84].

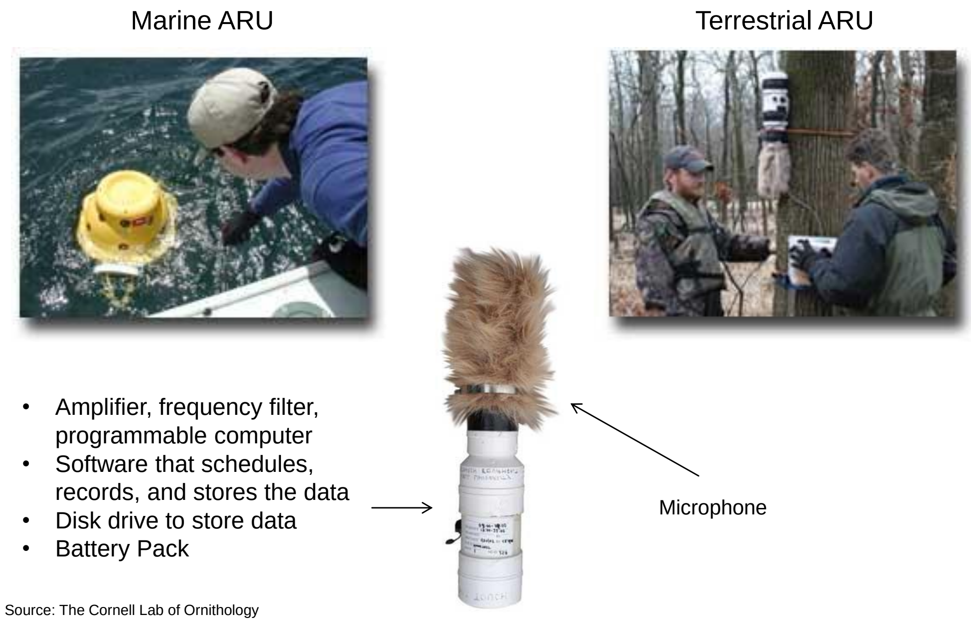


Figure 51 – Autonomous Recording Units for Wildlife Monitoring

Animal Tracking with Radio Tagging

Another active area of research in animal monitoring methods is the use of radio–tagging. An animal is fitted with a radio collar and antenna. The tag (image left in Figure 52) was developed by the Cornell University Laboratory of Ornithology and emits an amplified radio–frequency signal. Three or more receiver arrays (image right in Figure 52) may be used to precisely monitor tagged animals within the array. Each array precisely measures the time it detects a signal from an animal's collar[85]. Because the animal is a different distance from each receiver, the signal to each array can be used to triangulate and track an animal's location to within 200m.

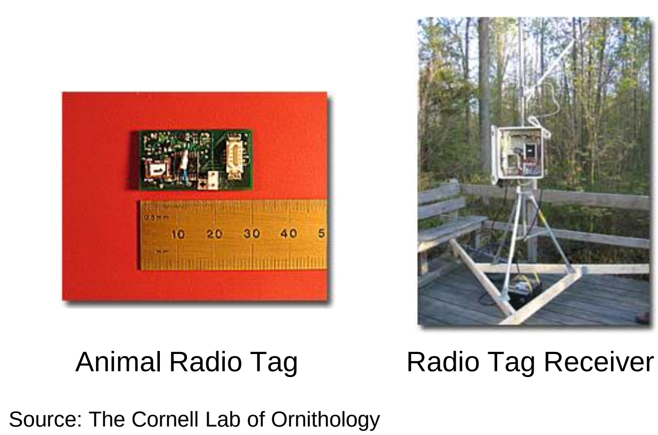


Figure 52 – Animal Radio Tag and Receiver

Animal Tracking with Unmanned Aerial Systems

For a number of challenging animal monitoring and tracking tasks, the use of autonomous recording and/or radio tagging is not practical. These tasks may include tracking animals or insects too small for radio tagging, tracking animals in remote or difficult to reach locations and monitoring animals over vast areas. Recent research into aerial tracking using unmanned aerial systems has produced a promising new solution.

Some of the more prominent research projects employing UAS are outlined in Figure 53. These include tracking tuna banks, tracking large mammals in challenging environments, and using UAS to track insect swarms for environmental research. One of the more interesting projects, recently sponsored by Google, employs UAS to track and deter illegal hunters around the world[86].

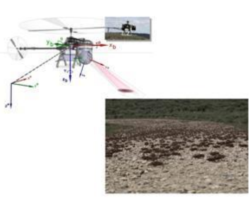
UAS Application to Animal Tracking and Conservation

THALES AEROVISION

- Aerovision Fulmar system (maritime model), marketed towards fisheries. Designed to assist fishermen finding tuna banks, due to its ability to perform sea-landing.
- Released in 2010

- The World Wildlife Fund (WWF) received a five million dollar grant from Google to expand its use of UAS to track and deter criminals who illegally hunt endangered animal species around the world.
- Program in Asia and Africa to protect rhinos
- Announced December 2012

- A team from Unité de Gestion des Ressources Forestières et des Milieux Naturels, Université de Liège Gembloux Agro-Bio Tech, Gembloux, Belgium recently used UAS to track elephants and large mammals in the south of *Burkina Faso*
- Announced February 2013



- A team from the Australian Center of Field robotics and the Australian Plague Locust Commission, developed a UAS to track individuals within a locust swarm to deliver data to the biologists to improve swarm modeling
- Announced 2007

Figure 53 – UAS Animal Tracking Projects

Case 5 – Detecting Disease, Drought, Insects and Invasive Species

Autonomous systems are proving to be a useful tool in agriculture and forestry for the detection of disease, drought, insects and other invasive species.

Fighting invasive plants and weeds

A number of research projects are using UAS to detect and fight invasive plants and weeds. Many of these projects are based in Australia due to the prevalence of many menacing weed species and open regulation regarding use of UAS. For example, in 2012, the Queensland State Government and the federal Department of Agriculture, Fisheries and Forestry (DAFF), engaged Boeing's Insitu Pacific in the fight against siam weed, a major environmental challenge in Australia[87]. The project deployed the Scan Eagle UAS (Figure 54) to survey the size and density of the siam weed population in Queensland. Other research projects have used UAS to autonomously detect and spray patches of weed. The Yamaha RMAX (Figure 50) is a common research platform used for weed detection and spraying research.

- Insitu Pacific, the Australia-based subsidiary of Insitu Inc., is deploying its ScanEagle unmanned aircraft system (UAS) on behalf of the Queensland Government for the detection of Siam weed, a major environmental challenge.
- *Boeing, June 2012*

- A team in Australia developed a Quadrotor to detect and autonomously spay woody weed, a major environmental threat in parts of Australia. Winner of the Australian Government "Defeating the Weed Menace program (DWM), competition.
- *ACFR, University of Sydney (2007)*

Figure 54 – UAS Project for Fighting Weeds

Fighting Plant Disease

A number of precision agriculture research projects are using autonomous systems to detect disease. The ability to rapidly identify and locate crops stressed due to disease or drought is of significant value to farmers. In 2012, the University of Florida initiated a project that uses a quadrotor equipped with multispectral imaging sensors to detect a form of citrus disease ravaging groves throughout Florida.

Other research by Virginia Polytechnic Institute and by Scotland's Forest Commission is focused on advancing methods for detecting and preventing the spread of fungal infection. A recent trial carried out by the Scottish Forestry Commission used drones to map the spread of phytophthora ramorum[88], a fungus which has recently spread from rhododendrons to larch, forcing forest managers to fell thousands of trees in a bid to contain the outbreak. Fungi are the most destructive form of biotic disease in forests and cause approximately 70% of all disease related forestry losses.

- University of Florida is developing a quadrotor platform with a multispectral imaging sensor to detect a citrus disease ravaging groves in Florida.
- *University of Florida* (2011)

- Virginia Tech has developed a UAS and ground sensor to detect and track blankets of fungal spores to determine risk of plant/tree disease, and even human health.
- *Virginia Tech* (2010)

- Scotland’s Forestry Commission Scotland is conducting a trial using UAS in the fight of forest tree rot by mapping the spread of a fungus
- *Announced October 2012*

Figure 55 – Select UAS Projects Involving Disease

Detecting Insects and Pests

Autonomous systems may also be used in the fight against insects. As described in Section 5.2.2, Voltree has developed a ground–based sensor that can be used within forests to detect signs of the Asian Longhorn Beetle. Other research involves detecting signs of insect damage by air. Each year, the US Department of Agriculture Forest Service conducts an aerial detection survey as a means of collecting and reporting data on forest insects, diseases and other disturbances[89]. Data is collected by aerial observers from the Forest Service. The method could be advanced by the use of UAS to potentially automate the data collection process.

Measuring Forest Parameters

In 2012, a team at the University of Tasmania developed an experimental MUAV–based LiDAR system, designed to measure (above canopy) forestry parameters, such as tree height, over small forest plots[90, 91]. Currently, such data can only obtained using industrial aerial LiDAR scanners that are economical over large areas only. The system was designed as a proof of concept, capable of only 3–4 minutes of flight. The system used an off–the–shelf OktoKopter MUAV platform and off–the–shelf sensor, initially designed for automotive industry. The system was able to generate detailed point cloud data at an altitude of approximately 50m. The accuracy of the IMU and sensitivity of the LiDAR sensor were the major limiting factors.

Figure 56 – Experimental Multirotor–copter Equipped with LiDAR

5.3 Regulatory Consideration

The market for civilian and commercial unmanned aircraft has been slow to emerge, primarily due to limited access to airspace. Defining safe UAS operations, setting realistic standards, achieving cultural acceptance and solving radio spectrum challenges are all issues faced by the unmanned aerial systems community and the Federal Aviation Administration (FAA). For UAS to be integrated into the National Airspace in a timely manner and for a positive impact on economic development to result, these issues need to be addressed[4].

Today, federal, state and local government entities must obtain an FAA Certificate of Waiver or Authorization (COA) before flying UAS in the National Airspace. Now, under the FAA Reauthorization Bill, the agency must to find a way to expedite that COA process within 90 days of enactment on May 14, 2012[92]. Regulations in countries other than the US vary significantly and no universal standards have yet been established (see Figure 58 for a review of international UAS regulation).

COA is an authorization issued by the Air Traffic Organization to a public operator for a specific unmanned aircraft activity. After a complete application is submitted, FAA conducts a comprehensive operational and technical review. If necessary, provisions or limitations may be imposed as part of the approval to ensure the unmanned aircraft can operate safely with other airspace users.

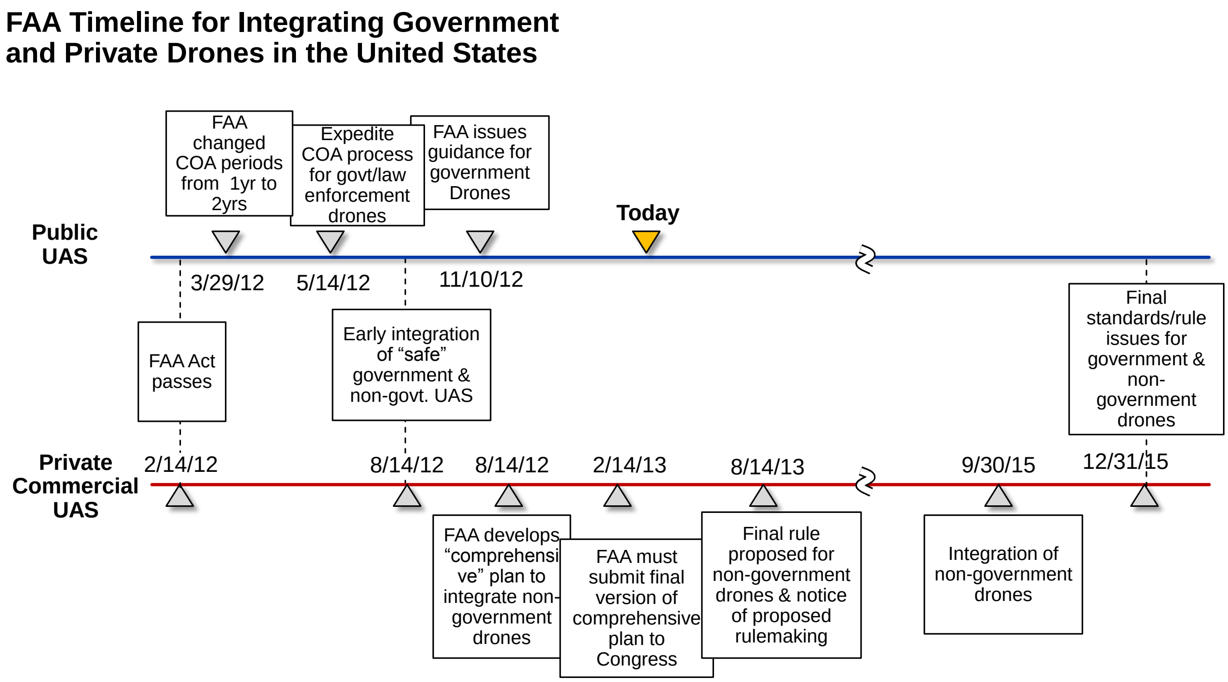


Figure 57 – Major Milestone and Timeline for UAS Integration into National Airspace System[93]

Country	Regulating Body	Regulation	Authorization	Purpose	Max Altitude	Collision Avoidance Conditions
USA	FAA	FAA Modernization and Reform Act of 2012 or P.L. 112-95	Certificate of Authorization (COA)	Public applications only - First Responders, Police, Fire Commercial applications not allowed	<400ft In class G Airspace	Line of sight of operator required
Canada	CAR	Canadian Aviation Regulations (CARs) 2012-1 Part VI - General Operating and Flight Rules 623.65(d) Unmanned Air Vehicle	Special Flight Operations Certificate(SFOC) Free to apply. SFOC requires detailed flight and safety plan	Any commercial activity, including testing, requires a Special Flight Operations Certificate approved 20 days in advance of flight	N/A	Evidence that flight plan is safe (i.e. away from personal and aircraft)
UK	UK CAA	UK CAP 722 guidance 5th Edition [August 2012]	UAS Remote Pilot licensing requirements (requirements undergoing development)	Public/civil and commercial applications	Not limited if using approved detect & avoid system Line of site: <400 ft	An approved detect & avoid/ collision avoidance system is required otherwise line of sight only
Australia	CASR	CASR Part 101 'Unmanned Aircraft & Rockets' [July 2002] New revisions currently underway [Project OS 11/20]	Require UAV controller's certification and an operator's certificate to fly.	Flown for air work, including commercial operations: - aerial photography - surveying - law enforcement .	400ft (AGL) Or higher with special approval	Operator must remain in radio contact at all times and remotely control aircraft using VFR/IFR rules
New Zealand	CAA	No Formal Regulation New regulation proposed but not yet underway	Special Authorisation from the CAA [only 8 authorizations currently in place]	Authorization under special consideration only i.e. - UAV for commercial films and photography from the sky	"below the obstacle clearance height at the airport"	N/A

Figure 58 – Review of International Regulation Regarding use of Commercial and Civilian UAS

6 Opportunity Identification and Prioritization

To identify opportunities, brainstorming workshops were conducted with forest managers, autonomous systems experts and forestry researchers. This chapter presents a short list of market opportunities discussed during workshops. High potential forestry management opportunities are discussed first in Section 6.1 and Section 6.3, whilst lower priority ideas are discussed in Section 6.3.

6.1 Top Market Needs and Opportunities

During workshops the top forestry technology needs were voted as following:

- More accurate, lower cost forest inventory methods
- More effective methods to detect disease
- More effective forest regeneration methods
- More efficient methods for measuring and auditing soil carbon
- More efficient methods for monitoring forest water quality

For each technology need, the team identified one or more opportunities corresponding to different potential product concepts. In the following sections, a brief evaluation of each of the high potential opportunities is presented based on the 'desirability, viability, and feasibility' selection filters described in Chapter 2. The top three 'high potential' market opportunities are selected for further discussion in Chapter 7.

6.1.1 More Accurate, Lower Cost, Inventory Analysis Methods

Forest inventory monitoring is an important task in forestry management. Today, accurate inventory data is measured through a combination of ground–based timber cruise and airborne or space borne remote sensing. There is a strongly expressed need to develop new technologies to reduce the cost and increase the accuracy of conducting an inventory.

Opportunity 1: Adverse Weather Condition Aerial LiDAR

Adverse weather conditions can pose a significant problem to aerial light detection and ranging (LiDAR) surveys. Cloud obstructs the laser signal emitted by LiDAR equipment, limiting the times an aerial survey missions may be conducted. Frequent cloud cover limits the number of days that expensive LiDAR equipment may be used (reduces equipment utilization), and thereby increases the overall end price of aerial survey services. This can pose a significant challenge in heavily forested areas in the north of America, Canada, and Alaska where adverse weather conditions are common.

Based on research, there is an opportunity to apply optimal path planning and navigation strategies as described in section 5.2.1 to mitigate the effect of adverse weather on aerial surveys. Such a technology could make it possible to conduct aerial surveys on partially cloudy days, thereby increasing equipment utilization.

Table 3 – Opportunity Assessment: Adverse Weather Condition Aerial LiDAR Market Opportunity

Desirability: High

- The need is real. The challenge of evaluating flight plans and re–flight plans to maximize area coverage during adverse weather conditions was recently discussed at the 2012 Geoscience and Remote Sensing Symposium[94].

Viability: Moderate

- Based on high level estimates, an aerial LIDAR sensor cost approximately $50,000 per month to own (Figure 72). Therefore, a technology that can be used to increase the utilization of such equipment, for example by increasing utilization during adverse weather days, has a value proposition to service providers and forest managers.
- The solution would need to compete in terms of effectiveness and cost with manual flight planning methods.

Feasibility: Moderate

- The technology to generate optimal flight path solutions is feasible.
- The technology to model cloud motion exists.
- From a regulatory perspective, there is moderate risk:
  - The solution could be integrated into existing aircraft without the need to remove the pilot, and therefore, the technology does not necessarily require new unmanned aerial vehicle regulation.
  - US airspace regulation requires that a fixed flight plan be logged. Flying a variable, dynamic flight path may require special permission.

Verdict: Top three opportunity

Opportunity 2: Small Footprint Aerial LiDAR for Field Plots

Due to the significant fixed cost associated with aerial LiDAR, aerial surveys are only financially practical when conducted over large areas. Ideally, surveys are conducted over 100,000 acres or more, depending on the data resolution required. The marginal cost per additional acre is relatively low.

There is a need, however, for a cost effective, small footprint aerial LiDAR solution for use on smaller survey areas, categorized by only a few hundred acres as opposed to thousands. In Section 5.2.2, we described one research team's effort to develop a solution to this challenge using a small profile LiDAR device originally designed for the automotive industry[90, 91]. This proof of concept system was only capable, however, of 3–4 minutes of flight.

Opportunities exist to explore new solutions to this challenge. For example, a solution may utilize 3–dimensional aerial photogrammetry, as described in Section 5.2.1 as an alternative to LiDAR. Alternatively, a solution may involve the use of beamed energy or battery change/recharge station, as described in Section 5.2.1, to help overcome the challenges associated with the significant power requirements of long range LiDAR sensors.

Table 4 – Opportunity Assessment Small Footprint Aerial LiDAR for Field Plots

Desirability: Moderate

- The need is real. However, given that large commercial forestry organizations frequently utilize wide area LiDAR surveys, the need is less urgent.

Viability: Moderate

- Whilst the technology is desired, and a financially viable product may be possible, the overall market size is difficult to determine.

Feasibility: Moderate

- Based on the proof of concept demonstrated by the University of Tasmania, the technology is possible.
- A number of challenges exist, including addressing power requirements and sensor accuracy at altitudes greater than 50 meters.
- From a regulatory perspective, the technology should be acceptable under the proposed 2015 FAA regulatory guidance, given the technology will operate below 400ft.

Verdict: Great opportunity but not top three

Opportunity 3: Below the Canopy Tree Metrology Systems

Tree diameter, tree taper and tree form are important metrics when evaluating the value of a timber stand. As described in Chapter 4, accurate measurement of these parameters requires manual field sampling by a trained forester, which is time consuming, costly and prone to sampling error.

There is a need to develop new solutions that either reduce the time required to conduct an inventory via the manual timber cruise, or that improve the accuracy of aerial measurement methods. In Section 4.3, we described the use of terrestrial LiDAR scanners as a promising new technology. Terrestrial LiDAR, however, has not yet proven cost effective, in part due to the limited field of view per scan.

Opportunities exist to explore autonomous solutions that utilize below the canopy mobile platforms to measure forest parameters. A platform may utilize a small mobile LiDAR scanner or an alternative sensor technology, such as a time of flight sensor. Furthermore, opportunities exist to use the same mobile platform and sensor to detect and measure growth defects, signs of disease and signs of insect damage, etc.

Table 5 – Opportunity Assessment: Below the Canopy Tree Metrology Systems

Desirability: High

- The need is real. However, given that large commercial forestry organizations frequently utilize wide area LiDAR surveys, the need is less urgent.

Viability: Moderate

- A viable business model could be developed if the technology could be shown to be more cost effective than terrestrial LiDAR methods and the traditional forest cruise. The technology could be sold or licensed to forest services or the technology could be sold directly to forest managers.

Feasibility: Moderate

- A number of technological challenges exist. For example, the technology for a micro–UAS to autonomously navigate through a complex forest environment is immature. However, based on the results by the team at Carnegie Mellon (section 5.2.1) the underlying technology is possible.
- From a regulatory perspective, the technology should be acceptable under the proposed 2015 FAA regulatory guidance given the technology will operate below 400ft. There are risks, however, that the advanced navigation technologies required may become export–restricted.

Verdict: Top three opportunity

Opportunity 4: Improved Species Recognition via Aerial Survey

A naturally regenerated forest may host multiple tree species. The mix of species can significantly impact the value of a forest, and therefore the future cash flows of a forest manager. Whilst technologies such as aerial LiDAR can now provide an accurate tree count, the determination of tree species using low cost aerial methods remains a challenge. Currently, species is predominantly determined through manual inspection by an experienced forester during a timber cruise. This approach, however, is limited to small scale surveys and is prone to sampling error.

There is a need for new technologies and methods to conduct wide area inventories, preferably via aerial survey, to accurately measure both tree count and tree species.

Table 6 – Opportunity Assessment: Improved Species Recognition via Aerial Survey

Desirability: High

- There is a strong need for an accurate method to determine tree species mix over wide areas.

Viability: High

- A strong business model could be built around any new, cost effective, and accurate automatic species recognition technology.

Feasibility: Low

- Research into tree species recognition via aerial survey has been an ongoing for the past 20 years. Most research has focused on the use of hyper–spectral data to identify tree species using vegetation spectra. This opportunity may be too challenging to address in a short time frame.

Verdict: Low feasibility

6.1.2 Soil Condition Monitoring

Opportunity 5: Monitoring Soil Condition for Timing of New Plantations

Prior to spreading seeds or planting tree seedlings when establishing a new stand, it is advantageous to measure the local soil properties, namely moisture content and temperature. Soil information can be used to optimize the planting strategy to maximize growth and minimize planting costs.

Currently, it is not cost effective to measure soil properties over vast areas on a frequent basis prior to establishing a new stand. As a result, forest managers are often forced to plant during less than optimal conditions due to lack of information, or forced to use less than optimal seedling stock for the prevalent soil conditions. Existing moisture measurement systems, such as those designed for precision agriculture[95], are configured for closely spaced mesh networks, and are not economically viable for large forested areas. There is a need for a new technology and/or method.

Table 7 – Opportunity Assessment: Monitoring Soil Condition for Timing of New Plantations

Desirability: High

- Planting costs average approximately 17% per cent (See Figure 95) of the total cost of managing a timber stand across the entire life of a stand. Therefore, any technology that can increase seed/seedling yield is desirable to a forest management firm.

Viability: Moderate

- The technology would need to be cost effective over vast areas, i.e. thousands of acres. The business case is sensitive to the cost of the solution.

Feasibility: Moderate

- There is an opportunity to apply modern sensor network technologies (Section 5.2.2 – Case 1) to the challenge of monitoring soil condition prior to reforestation activities.
- Alternatively, there is a potential to utilize a UAS to remotely sense soil information methods. For example, by using a thermal camera to monitor surface temperature, and an L–band radar to estimate soil moisture water content [96].

Verdict: Top three opportunity

6.1.3 Measuring Soil Carbon

Opportunity 6: Measuring Soil Carbon

The forest soil carbon sink is of potentially great monetary value to forest owners, but the cost of reliably monitoring soil carbon remains a challenge[97]. Soil carbon represents up to 60 per cent of the total carbon stored in a forest, and changes in the carbon stock must be reported as part of the national greenhouse gas reporting on the Climate Convention (UNFCCC2001, IPCC 2003). Furthermore, carbon sequestration projects under the Kyoto Protocols require that stand scale changes in the vegetation and soil carbon stock are validated before the obtained carbon sinks are eligible for credit in carbon markets.

Today, organic layer measurements cost approximately 520 Euros ($680) per plot, based on 10 soil samples per plot[98]. Approximately one sample plot is required per 25,000 acres of forest for adequate monitoring. Therefore, a more cost effective method to measure soil carbon would be of tremendous value to public and private forest managers interested in participating in any carbon accounting and trading scheme.

Table 8 – Opportunity Assessment Measuring Soil Carbon

Desirability: High
- There is a strong need to accurately and cost efficiently measure forest soil carbon content.

Viability: High
- A viable business model could be developed around any new cost effective method.

Feasibility: Low
- The determination of forest soil carbon has been an ongoing area of research for the past 20 years. It is unclear how autonomous systems may be applied to progress current research activities.

Verdict: Low feasibility

Image courtesy Alex McBratney, University of Sydney, Australia

Figure 59 – Field NIR Profiler for Soil Carbon Measurement

6.1.4 Water Quality Monitoring for Regulation

Opportunity 7: Water Quality Monitoring for Regulation

Although forest water quality management in the US is regarded as excellent, some forest management practices can seriously impair stream water quality. Sediment from logging activity is the main concern, although nitrate and water temperature impacts are also of concern in some locations.

Figure 60 - Portable Foresters Water Quality Kit

Furthermore, as housing development continues to extend into private forested land, there is an increased risk of impact to forest watersheds (Figure 61). Forest managers, therefore, must monitor and test forest watersheds on a frequent basis. The measurement process, however, is manual and a more automated or autonomous method for collecting samples and testing water quality is desirable.

Table 9 – Opportunity Assessment – Water Quality Monitoring for Regulation

Desirability: Moderate

- Whilst there is a need for a lower cost water monitoring method, existing monitoring practices and equipment suffice.

Viability: Low

- A business model or sales proposition is unclear in light of competing products.

Feasibility: Moderate

- A number of technology solutions already exist, such as the use of permanent water monitoring platforms.
- There exist a number of guidelines with respect to the management of forest watersheds. A successful new product would need to adhere to the guidelines.

Verdict: Low viability

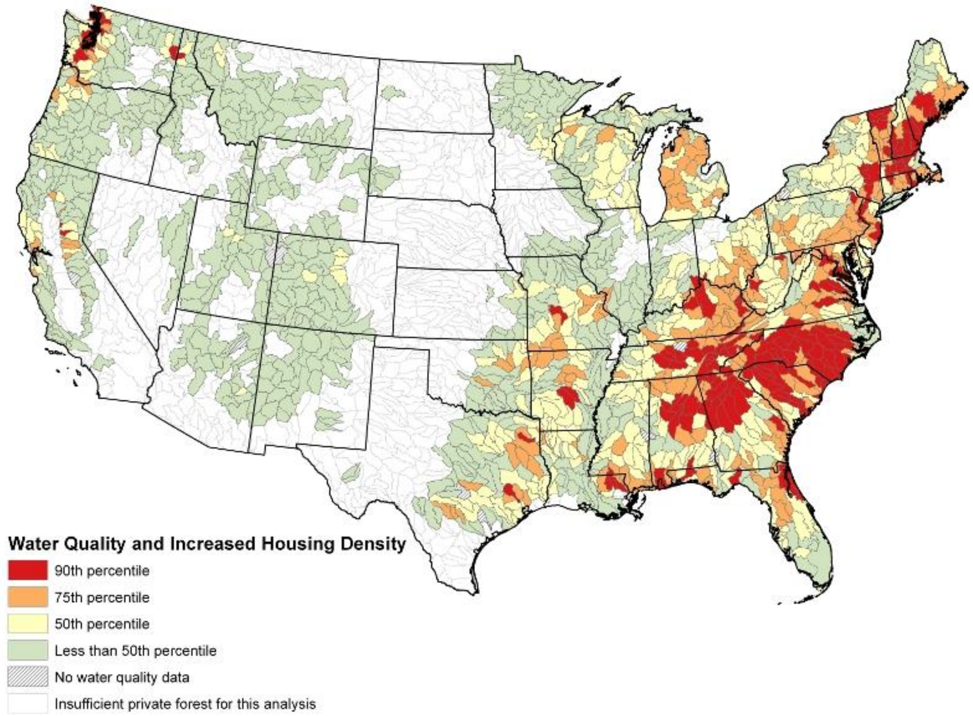


Figure 61 – Watersheds by potential for changes in water quality as a result of projected increases in housing density on private forest lands[99]

6.2 General Considerations for Evaluating Opportunities

Based on discussions with forest managers, the following considerations were noted as specific design challenges:

Data Retrieval Challenge: Once a remote sensor is deployed in the field, it becomes a challenge to retrieve any data collected. Satellite connectivity such as through the Iridium network is expensive. Furthermore, many forested areas are not within range of the cellular network. Mesh sensor networks are an option, assuming one node in the mesh can connect to the cellular or satellite communications network. Mesh networks, however, are only suited to applications that require a high density of sensors, such that each sensor can communicate with at least one other adjacent sensor. The data retrieval strategy must be considered in any system design.

Equipment Damage Challenge: Any equipment left in the field (i.e. remote sensing platforms) needs to be rugged, resistant to animals and the elements. Furthermore, they are only suitable in forests that do not host any hunting activity. Based on feedback from commercial forest managers, any expensive equipment (especially when hidden and camouflaged) makes good target practice for hunters.

6.3 Additional Market Opportunities

A number of good opportunities were raised during workshops that were not selected for detailed consideration. Many of these ideas fell outside the scope of forestry management. Whilst they were ultimately not prioritized, many of these ideas may warrant future research and are therefore described below in brief.

<u>Hazing of Birds at Fisheries</u>

Birds and mammals that prey on salmon smolt and other fish species can pose a significant challenge for many commercial fish farms. A potentially desirable solution would involve a system that autonomously monitors fish farms to detect the presence of such birds, and autonomously deploy small unmanned vehicles to haze and harass birds away from smolt/fish.

<u>Monitoring Insect Populations</u>

An important but challenging conservation task is the monitoring of insect populations at various heights to gauge the food supply for aerial insectivores.

An unmanned vehicle could be configured to sample flying bugs at various heights in order to address this difficult data collection task.

<u>Monitoring Intertidal Shrimp Beds and Algae Mats</u>

Monitoring intertidal shrimp beds and algae mats is a manual but important task. Increased growth of algae mats due to organic runoff is causing some population of shrimp species to collapse. As algae mats grow during the summer, the algae uses up vital oxygen in the water, killing shrimp, eel grasses and worms and depleting food for other wildlife such as fish and birds.

Algal bloom on the shore of Langstone harbor in Hampshire, that has destroyed the local ecosystem

Today, researchers monitor these estuaries by walking around the beds with hand held GPS devices. The current method is tough, time consuming, and can only be used to monitor a limited number of locations. An autonomous system capable of monitoring a greater area is desired.

Monitoring Eagle Nests for Conservation

Eagle nest locations are well known, but are often difficult to reach due to their wide geographic spacing and hazardous location.

The nests are typically visited twice per year to determine 1) whether they are active, and 2) reproductively successful.

It would be advantageous to develop a UAS designed to help collect data from nests without disturbing the habitat. Such a system could save a human life. Each year approximately 1–2 biologists die in the US from counting or monitoring animals in hazardous locations.

A biologist bird researcher climbs to monitor a Golden Eagle nest for important conservation purposes.

Deploy environmental stations/sensors and download data

A UAS could be designed to deploy environmental monitoring stations, either on land or in the ocean, to monitor animal populations or to collect other important information.

Another UAS could be configured to fly over the stations to download data from the remote stations as an alternative to satellite connectivity or manual data collection from the field.

Autonomous recording unit (ARU,) developed by Cornell University to remotely count bird species

Aerial winter surveying of animal populations

The use of aircraft to survey animal populations has proven successful. Aircraft were recently used to reveal a previously unknown population of the endangered pygmy rabbit.

Flying traditional aircraft is costly, and cruising at low altitudes is poses a risk for standard piloted planes due to risk of collision with hills, trees and other obstacles.

A low cost UAS system could be a safer alternative.

New populations of endangered pygmy rabbits recently discovered using low altitude airborne surveying.

Tracking and Locating Feral Hogs

Feral hogs are estimated to cause nearly $1 billion in damage nationwide in the USA each year[100]. Feral hogs eat everything in sight, including deer fawns, ground–nesting birds, crops and nuts and fruit that wildlife need. Furthermore, they carry diseases like pseudorabies that are fatal to pets and livestock.

Feral hogs cause $1 billion in damages per year in the U.S.

Feral pigs are also incredibly elusive and challenging to track. Past efforts by the Oregon Department of Fish & Wildlife to collar hogs to locate large groups have not proven effective.

A low cost drone capable of reconnaissance – especially at night when the pigs are active – would be a tremendous help. The shape of the pigs would make them easy to distinguish by air.

Monitoring and Management of Forest Mesocarnivore populations

Many mesocarnivores (including the coyote, badger, red fox, etc) are secretive and nocturnal, making visual detection difficult or impossible. Surveying for animal sign (tracks, scats, hair, dens, pug marks, etc.) in forests can be an effective method for establishing species presence and, therefore, distribution.

Mesocarnivore tracks (sign)

Many agencies use trained professionals on snowmobiles to detect tracks/signs of mesocarnivores, however, this is costly. UAS could be used to increase the scope of a survey in a more cost effective manner. A UAS could also address many other factors that frequently scuttle data collection efforts, such as the sound of a snowmobile.

Detecting and Monitoring Tsunami Debris

The March 2011 Japanese tsunami disaster washed about 5 million tons of debris into the sea. Much of this debris is still afloat and will wash up on North American coastal areas. A major concern by environmental agencies is hazardous or large debris beaching in remote areas and going undetected.

In 2012 the National Oceanic & Atmospheric Administration received a $5 million donation from Japan to track and remove tsunami debris.

A UAV could be configured to study and monitor hard–to–access areas of coastline for large tsunami debris.

Detecting Illegal Activity

Illegal activity, in particular the growth of illegal cannabis plants and other illegal drug products, is a rampant issue within remote public forest lands and Indian reserves. In 2011, the United States Drug Enforcement Administration removed 6,226,280 plants from public forests, seized $42.1 million of cultivated crops and removed 5,181 weapons from cannabis cultivators located in forests. This represents only a fraction of the total illegal activity.

UAS could be an effective and significantly safer method for detecting and collecting data on illegal operations hidden within forests.

7 Concept Generation: Three Case Studies

In this chapter we expand on the three high potential forestry opportunities identified in Chapter 6. We discuss the customer needs analysis from workshops and interviews and propose a number of potential systems concepts, leveraging the technology reviews conducted in Chapters 4 and 5. This chapter is a culmination of the research presented each of the previous chapters.

7.1 Concept I: Adverse Weather Condition Aerial LiDAR

7.1.1 Opportunity Description

A number of commercial forests in North America are situated in regions that are subject to frequent and often low–lying cloud cover (Figure 62). Unfortunately, low–lying cloud can pose a problem for forest aerial LiDAR surveys. Even small patches of cloud can generate gaps in the survey data, which can lead to challenges when processing and analyzing[101].

Cloud obstructs the laser signals emitted by LiDAR equipment, limiting when aerial missions may be conducted and limiting the total number of possible aerial missions per year. Due to the significant fixed costs associated with LiDAR equipment (Figure 72), including hardware costs, insurance and management costs, and cost of employing professional equipment operators, it is desirable to maximize equipment utilization throughout the year and minimize downtime due to adverse weather or cloud.

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Example: low lying cloud over forest   Example: broken widely spaced cloud

Figure 62 – Illustrative Broken Cloud Patches over Forested Land

PEGASUS HA500 by Optec

Net weight of sensor: 65kg

Net weight of control rack: 46 kg

Power requirement: 28 V, 800 W, 30 A.

Basic components of an airborne LiDAR system

- Laser scanner system
- Laser cooling system
- High accuracy Global Positioning System (GPS) and timing clock
- Inertial Navigation System (INS)
- Position and orientation system
- Inertial confinement system (i.e. roll compensation)
- Aircraft mounting frame
- Data storage
- Power system/regulator

Figure 63 – Example Airborne LiDAR Mapping Technology

7.1.2 Concept Description

General Description

The proposed system utilizes dynamic path planning methods to modify the aircraft's flight path 'on–the–fly' to seek out areas free of cloud. The concept adapts advanced path planning algorithms and methods initially developed for autonomous mobile systems in the presence of fixed or slow moving obstacles. For this particular implementation, obstacles are scattered clouds with semi–predictable motion.

The path planning algorithm attempts to solve the problem of maximizing the area surveyed, whilst minimizing expected flight time, subject to the boundaries of the survey site. The path planning algorithm takes into account cloud position and cloud motion as measured by a ground based all sky imager, small unmanned aircraft or other data source.

The system may be implemented into a controller that interfaces with modern autopilot systems. In this regard, the proposed system need not replace the physical pilot entirely, thereby avoiding current regulatory issues pertaining to the use of unmanned aerial vehicles and potential future regulation limiting the use of commercial UAS to below set altitudes. Furthermore, the system may be implemented into existing light aircraft and equipment as a retrofit option, thereby enabling adoption throughout existing aircraft fleets used for aerial surveys. In future revisions, the system may be implemented into a fully unmanned and autonomous solution as UAS technology and government regulations evolve.

The Path Planning Process

Today, flight paths for aerial surveys are pre–planned and typically follow a grid like pattern as depicted in Figure 64. The figure illustrates an actual recorded flight trajectory of a wide area, low resolution, forest survey. LiDAR data was collected on the portions of the path colored in purple. Such a flight path is efficient on clear sky days, but not necessarily efficient on partially cloudy days. Figure 63 on the following page illustrates how a dynamic path may be more efficient than a static path on partially cloudy days.

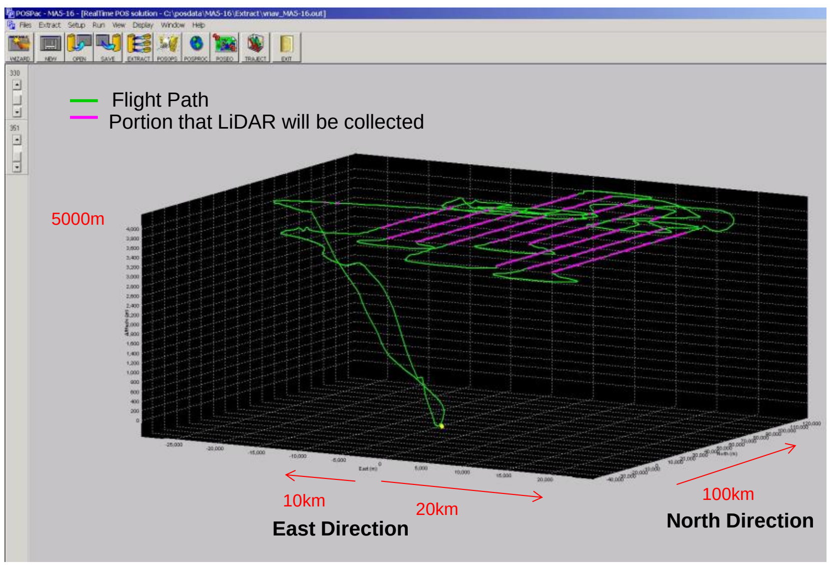
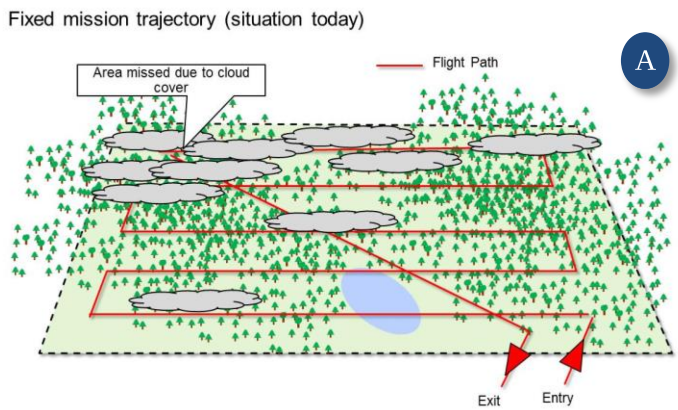
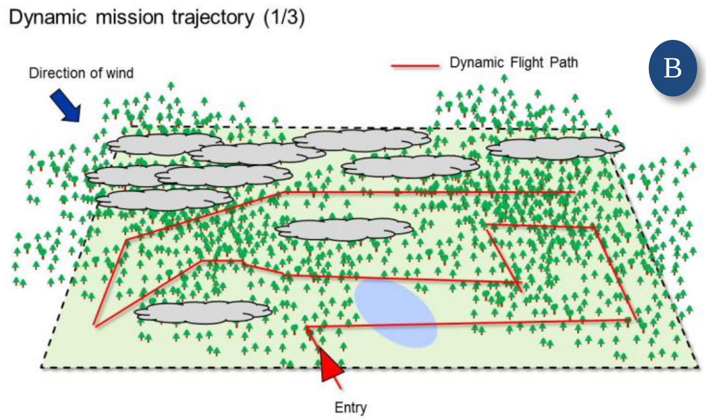


Figure 64 – Airborne LiDAR Flight Trajectory

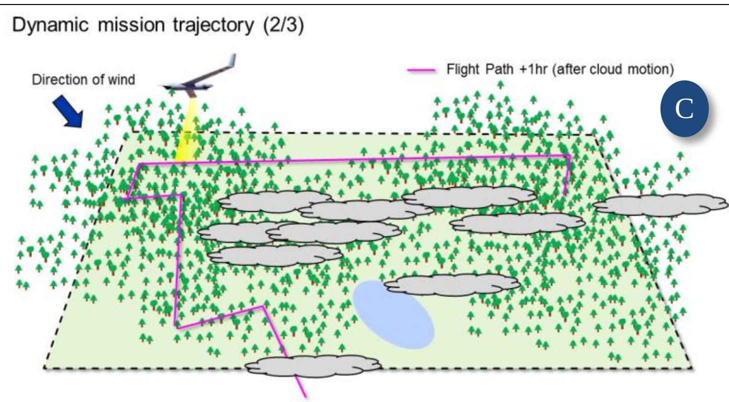


Today, flight paths are pre–planned and typically follow a grid like pattern.

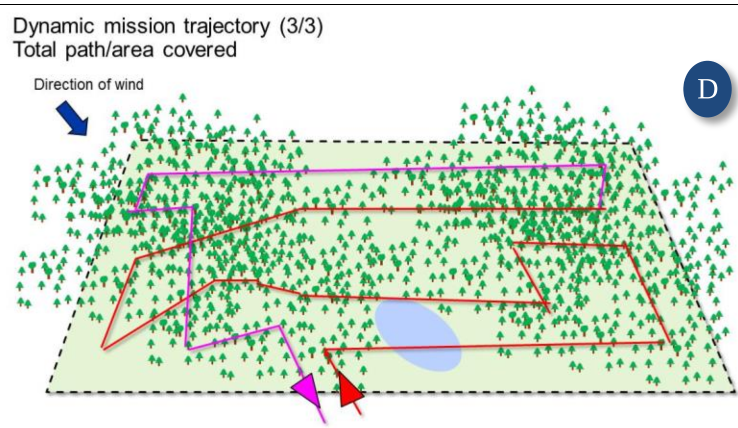
In the illustrative diagram, ~30% of forested area is missed using the static flight plan due to the cloud cover.



A dynamic path navigates around cloud cover…



… as clouds move, the path is adjusted to traverse areas not yet surveyed



In this illustrative example, the dynamic flight path covers more forested area than the static path without significantly increasing the distance travelled.

Figure 65 – Illustrative Dynamic Path in the Presence of Broken Cloud

7.1.3 Needs Analysis

Based on discussions with forest managers and aerial LiDAR service providers, the following list describes the most important requirements (customer needs) for the proposed system. This list can be roughly mapped to the requirement categories described in Section 2.1, Figure 7.

Overarching Need: The system is required to increase utilization of aerial LiDAR equipment by enabling more forestry surveys to be conducted on adverse weather/ partially cloudy days.

- *Capability*: The system needs to increase the percentage of land successfully surveyed within the boundaries of the survey area on partially cloudy days.
- *Capability*: The system needs to either match or reduce the airtime required to conduct the survey mission with respect to manual methods on partially cloudy days.
- *Capability*: The survey data quality must be equal to or greater than data from current survey methods.
- *Adaptability*: The system should be compatible with existing aircraft fleets given that turnover rate of aircraft is low (i.e. the system should integrate with modern light aircraft autopilot systems).
- *Reliability/Survivability*: The system needs to be reliable and robust under a variety of cloud conditions/types.
- *Maintainability*: The system needs to be maintainable by the same skill–set required to install and maintain existing aerial LiDAR systems.
- *Affordability*: The system needs to be cost effective with respect to existing methods. That is, the system cost must not exceed the value generated through improved equipment utilization.

7.1.4 Functional Requirements

Whilst the customer needs describe the desirable properties of the system, the functional requirements describe how those needs are addressed. For brevity, only the most important requirements are discussed here.

Improved Survey Efficiency

To address the need for improved survey efficiency (area coverage vs. time) on partially cloudy days, the proposed system utilizes autonomous path planning and control methods to navigate scattered clouds in a more efficient manner. The following list describes a subset of requirements for this capability:

- The system is required to generate an efficient and dynamic path through scattered cloud cover, subject to the objectives and constraints of the aerial survey:
    - The system is required to monitor and identify gaps in cloud cover in the local vicinity of the survey area.
    - The system is required to model and predict cloud motion given prevalent weather conditions.
    - The dynamic path planning algorithm must take into consideration the kinematics of the aircraft and LiDAR system. For example, the maximum rate of climb should never be exceeded.

Acceptable Survey Quality

Data quality can be broken down into a number of important requirements:

- The LiDAR surface point density must meet the minimum requirement for the given survey mission objectives.
- The variability in surface point density should be minimized.
- The system should minimize gaps in the LiDAR point cloud:
    - The path planning algorithm should generate an acceptable level of sidelap.
    - The path planning algorithm should minimize gaps in total area coverage as a result of the path flown (i.e. does not leave areas not surveyed).
    - The path planning and control algorithm should avoid steep turns that interrupt smooth data collection.

Surface Point Density

Of the above requirements, the concept of average surface point density and its relationship to data quality is of importance. Average surface point density refers to the average number of LiDAR laser pulses per square meter of ground. Figure 66 illustrates the impact of surface point density on the resultant point cloud.

It is important that the dynamic path planning controller/autopilot maintains a constant average scanning point density that exceeds the required (minimally acceptable) threshold for the particular survey objective. Inadequate density or variability in the average surface point density can lead to challenges when extracting features from the raw data [101].

A paper entitled 'Minimum LiDAR Data Density Considerations for the Pacific Northwest' by Watershed Sciences, Inc. [102], states the following recommendations for the minimum acceptable surface point density for common forestry needs:

Table 4 – Recommended LiDAR Point Densities for Forestry Metrology

	Recommended Resolution (pulses per square meter)	
	Minimum	Desirable Target
Tree Species Identification	4	6
Forest Measurement and Monitoring	4	4
Tree Height Measurements	4	6
Vegetation Characterization	4	8
Digital Terrain Model Accuracy under Canopy Cover	4	6

Figure 66 – Example Side Profile of Forest LiDAR Data: 8 pulses per m^2 vs. 0.25 pulses per m^2

A number of factors, including both speed and altitude (above ground level), will influence surface point density. Because an efficient flight path may require frequent changes in altitude and speed, the functional requirements associated with surface point density call for an integrated controller that manages both path planning, aircraft control and LiDAR system control. The relationships between surface point density, aircraft speed, aircraft altitude and LiDAR system parameters are better explained by Table 5 and the equations of Figure 67.

Table 5 – Parameters Influencing Point Density

	Parameter	**Typical Range**	**Impact on Surface Point Density**
Aircraft parameters	Operating altitude above local ground level	200 – 4000m	↑faster ↓lower
	Aircraft speed (knots)	10 – 140knots	↑faster ↓lower
LiDAR system parameters	Scan frequency	0–100Hz	↑faster ↑higher
	Scan half–angle (deg)	0 – 30^{o}	↑wider ↑lower
	System pulse rate frequency (kHz)	5 – 150khz Max frequency is *f(Altitude)*	↑faster ↑higher

Aircraft Setting		LiDAR System Settings (desired)		Point Cloud Results (calculated)	
Altitude (mt)	1000	System PRF (Hz)	107800	Swath (mt)	352.7
Altitude (feet)	3280.84	scan Freq (Hz)	63.8	Crosstrack (mt)	0.4
Speed (knot/h)	90	scan half angle (±deg)	10	Downtrack (mt)	0.4
Speed (mt/sec)	46.2996			Resolution (mt)	0.4
Overlap (%)	25			Point Density (1/mt^2)	**6.6**
Overlap (mt)	309				

= system input (yellow)
= system output (blue)

- Swath width (m) = 2* [Altitude * (TAN (half angle) * PI() / 180)]
- Cross track (m) = (2 * scan Freq * swath) / system PRF
- Down track (m) = (speed / scan freq) / 2
- Resolution (m) =√(cross track * down track)
- Point density (1/m^2) = 1/ cross track * down track

Figure 67– Basic Mission Planning Calculation

Acceptable sidelap equivalent

Sidelap refers to the percentage of overlap between adjacent scanning swaths. In order to minimize the risk of gaps in data collection, as illustrated in Figure 68, most survey operators will try and acquire LiDAR data with up to 50 per cent sidelap. The path planning algorithm of the proposed system should minimize gaps in data collection by targeting a minimally acceptable sidelap.

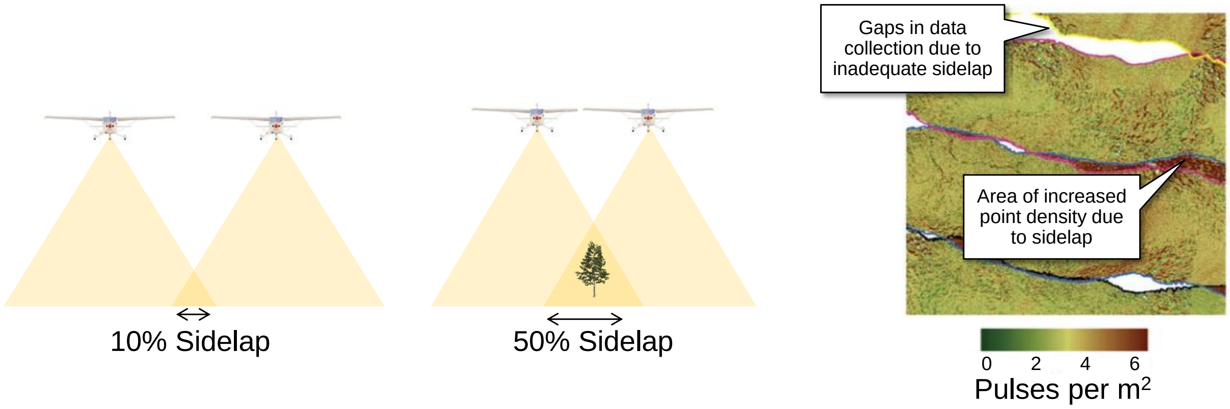


Figure 68 – Illustration of Sidelap and Impact on Data Collection

7.1.5 Description of System Elements

Figure 69 depicts the various system elements of the proposed illustrative embodiment.

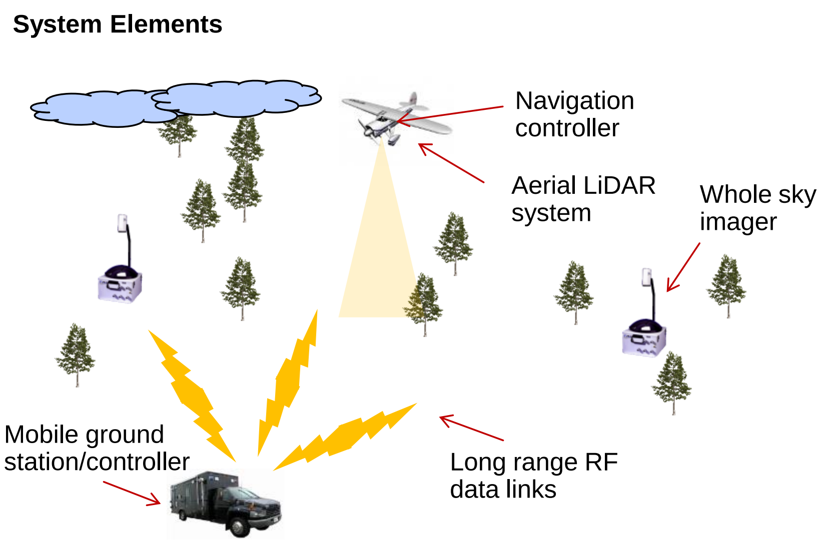


Figure 69 – System Elements of Adverse Weather Condition Aerial LiDAR

Cloud Monitoring Subsystem

There are a number of methods for monitoring cloud cover over large areas. One solution is to use a device known as a whole sky imager. Such a device can monitor cloud coverage over approximately 40,000 acres, depending on the height at which it is mounted. Over larger areas (a survey may be as large as 100,000 acres), or in mountainous regions, more than one imager may be required for full coverage of the survey area. Given the relatively

Whole Sky Imager by Scripps Institute of Oceanography

16 bit digital imaging system that acquires images of the full sky (2p hemispheres) under both day and night conditions to assess cloud fraction, cloud morphology, and radiance distribution

Figure 70 - Whole Sky Imager

low cost and transportability of the device, multiple whole sky imagers could be strategically positioned prior to any aerial survey.

A second option for the monitoring of cloud cover involves the use of a smaller 'scout' UAS. The UAS may fly in collaboration with the primary aerial LiDAR aircraft to map out prevalent cloud cover over the survey area. A third option is to use satellite imagery to monitor cloud cover; however, this approach is subject to the availability of detailed satellite data at the time of the survey.

Ground Station

A mobile ground station may be used as a centralized control center. The station receives data from multiple whole sky imagers (or scout UAS) via long range radio communication links or other communications networks. The station's computer processes cloud data, runs predictive modeling of cloud motion and calculates the efficient path for the aerial survey vehicle.

Navigation Controller

The ground station transmits the optimal path to an onboard navigation controller situated inside the aircraft. The navigation controller uploads the path into the vehicle's autopilot in the form of way–points, or other means. Furthermore, the navigation controller adjusts the settings of the aerial LiDAR system to ensure the minimum surface point density is maintained.

7.1.6 High Level Business Case

Today, Aerial LiDAR services for timber inventories are roughly priced between $1.63 and $3.79 per acre in America's north west, including data processing fees[103]. These estimates are based on a mean pulse density of 6.3 pulses per meter squared. The equivalent cost per acre for a manual timber inventory is $2.55. This figure is based on manual surveying of 18 per cent of the forest area[103].

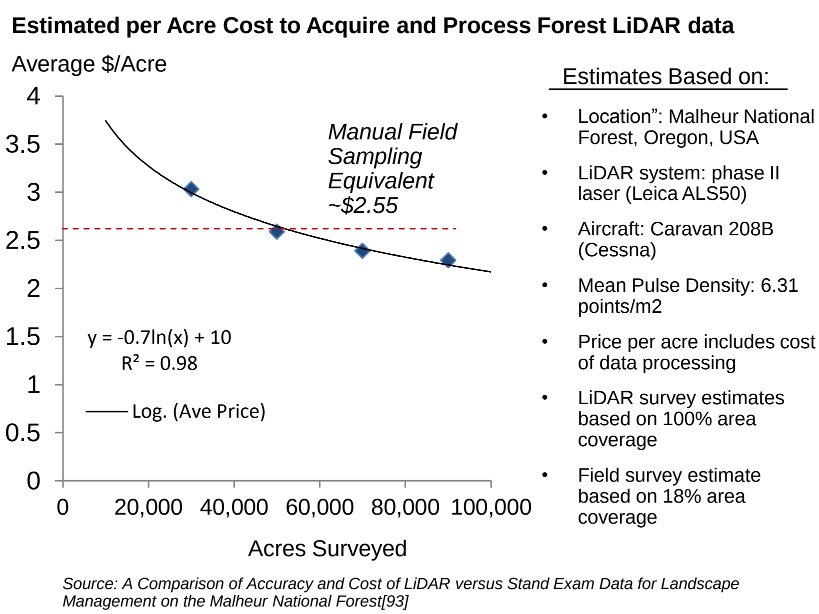
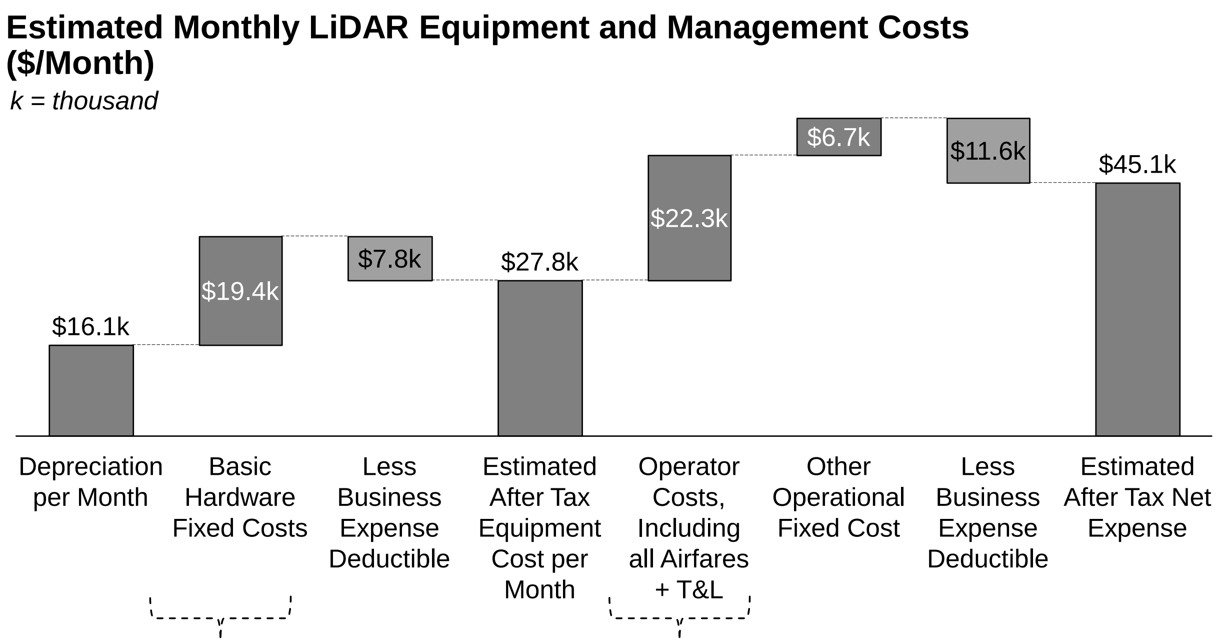


Figure 71 - Estimated per Acre Cost to Acquire and Process LiDAR Data[93]

An effective business case for the adverse weather LiDAR system should consider the impact on the cost per acre metric from both the aerial service provider's perspective and the end customer, the forest manager's perspective.

To understand the business case, we first need to understand the baseline equipment costs and the potential increase in equipment utilization. Figure 72 illustrates a rough cost break down of the fixed costs associated with owning and operating a LiDAR sensor. The estimated net after tax cost of ownership is approximately $45,000 per month for a system similar to that depicted in Figure 63. The estimate is based on cost of ownership for the sensor only and excludes aircraft rental and pilot costs.



Fixed Costs	
System Warranty at $125,000/yr. per person	$11.3k
System Insurance	$2.2k
Administrative, Logistic, Legal, SG&A, & IT/MIS	
Logistics & Planning	$4.8k
Legal, Except Export Licensing	$1.1k
Net Basic Hardware Costs:	**$19.4k**

Fixed Costs	
Calibrations, Testing & Local Maintenance	$5.1k
Hangar Costs	$1.6k
Other Operational Costs:	**$67.k**

†Assumes that all monthly management fees are deductible as business expense
†Assumes 40% corporate tax rate
† Laser System Acquisition Cost of $1,356,524
†Assumes 7-year straight line depreciable asset class for laser system
Data source: airborne1.com

Note: aircraft and pilot costs are considered variable and excluded from the cost breakdown. Costs can be significantly greater for state–of–the art sensors and costs may also be influenced by the number of persons required to operate the equipment

Figure 72 – Typical Fixed Cost Breakdown for Aerial LiDAR Technology

To understand the potential value proposition for the proposed system, we assess the number of mostly sunny and partially cloudy days per year by region. The National Oceanic and Atmospheric Administration categorized cloud cover into four classes: mostly sunny (less than 10 per cent cloud cover), partially cloudy (10 –50 per cent cloud cover), cloudy (51–90 per cent cloud cover), and dreary (91–100 per cent cloud cover). Today, aerial LiDAR missions are best suited to mostly sunny days.

Heavily forested regions such as those based in Washington State and Oregon, experience as few as 88 mostly sunny days per year (less than 25 per cent of the year). Furthermore, periods of significant high probability of sunny days are limited to only a few months each year. As a result, demand for aerial LiDAR equipment during these months is inflated. The proposed system makes it possible to conduct LiDAR missions on more partially cloudy days. The system, however, will not be effective on days characterized by greater than 50 per cent cloud cover. Note that the proposed system may not be applicable to all partially cloudy days. For example the system will not provide any benefit when the cloud ceiling is high enough such that the survey may be conducted below the cloud.

	Mostly Sunny (Clear)	**Partially Cloudy** (Broken clouds)	**Cloudy** (Scattered Clouds)	**Dreary Days** (Overcast)
% Cloud Cover:	<10%	10% - 50%	51 to 90%	91%-100%
Month:				
October	8	15	8	0
November	3	9	12	6
December	1	16	8	6
January	0	10	14	7
February	7	6	12	3
March	5	8	17	1
April	4	13	13	0
May	9	4	18	0
June	7	9	14	0
July	13	7	11	0
August	17	11	3	0
September	14	9	7	0
Total	**88**	**117**	**137**	**23**
% of Total	**24%**	**32%**	**38%**	**6%**
Conditions Suitable for Dynamic Path Planning LiDAR:	✓	✓	✗	✗

Source: http://www.olympicrainshadow.com; http://www.noaa.gov/

Figure 73 – Analysis of Cloudy Days in Forests Surrounding Seattle

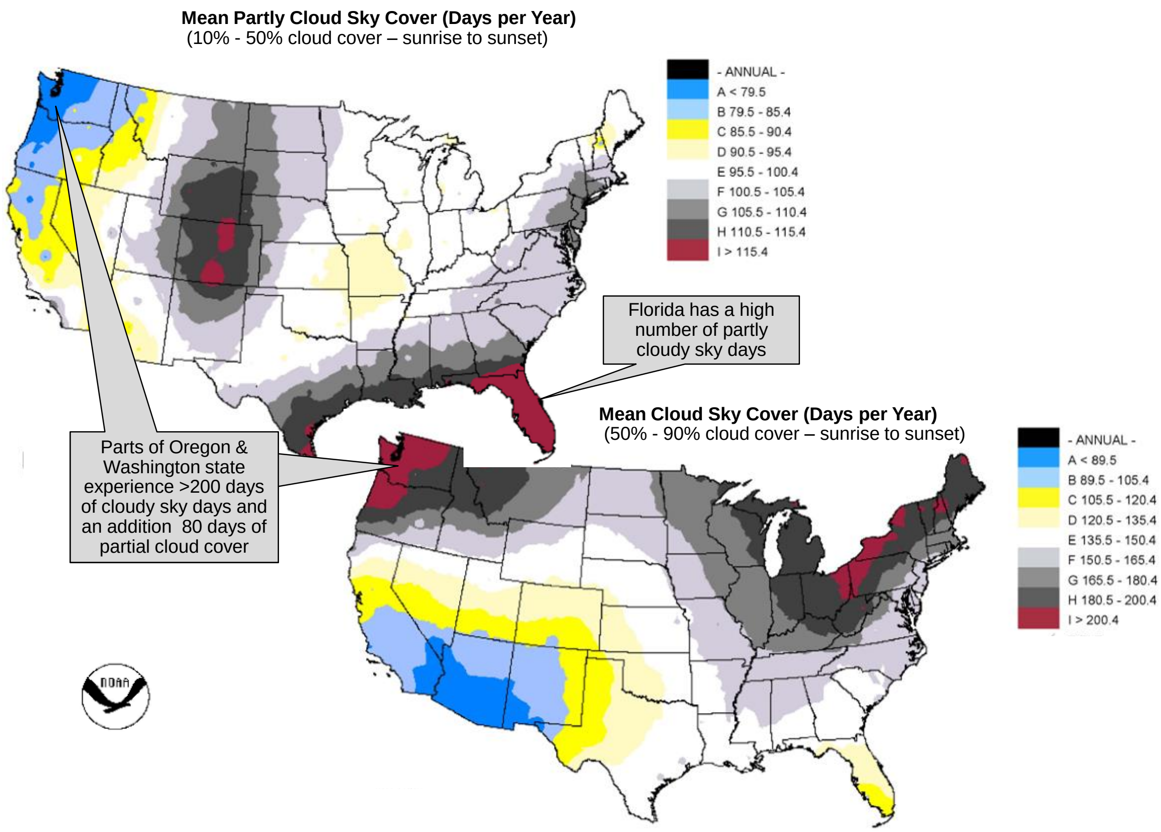


Figure 74 – NOAA Analysis of U.S. Average Cloud Cover

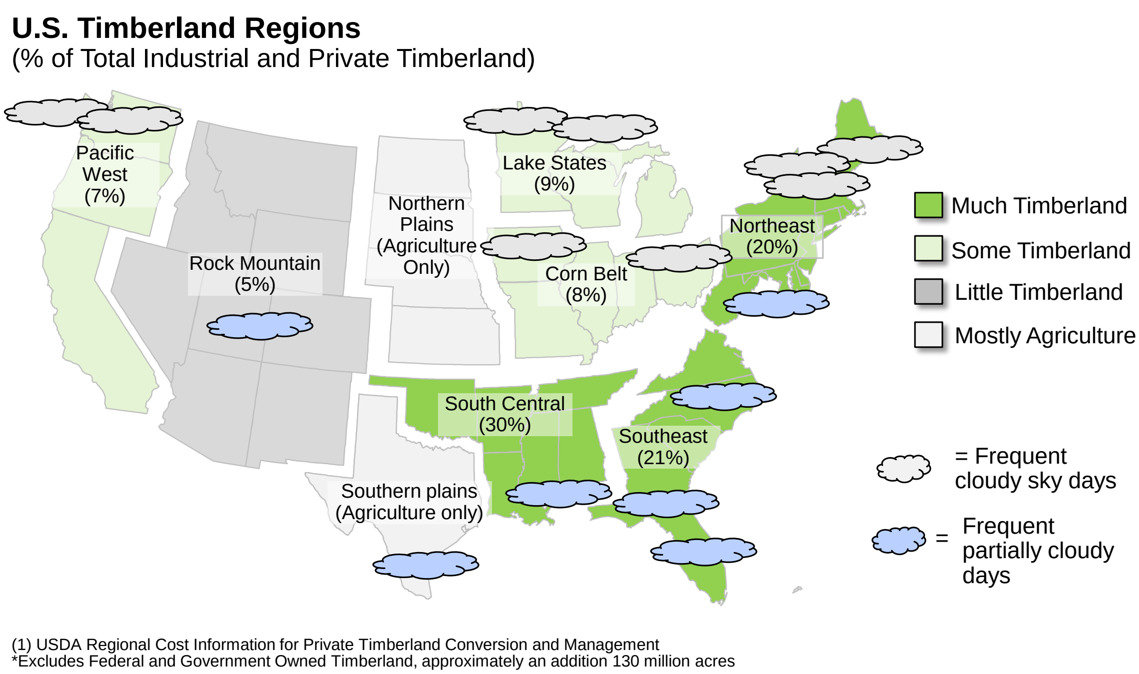


Figure 75 – Overlay of Mean Conditions on U.S Forested Regions

Based on the above analysis of the count of partially cloudy days in areas with significant commercial timberland, the proposed system is estimated to increase LiDAR equipment utilization by up to 20 per cent, subject to demand and effective equipment scheduling. A rough lower bound estimate for the value delivered by the system therefore equates to approximately $100,000 based on the annual cost of equipment ownership per LiDAR system per year.

- Equipment Cost per Month = $45,000
- Annual Cost = $540,000
- 20 per cent of Annual Cost = $108,000

7.2 Concept II: Below Canopy Tree Metrology Systems

7.2.1 Opportunity Description

Tree diameter, tree taper and tree form are important metrics when evaluating the value of a timber stand. These measurements, however, are difficult and costly to determine, and are typically measured by manual timber cruise or via empirical models based on average tree height.

Sending a forester into the field to conduct a timber cruise is both time consuming and costly. Furthermore, estimating tree diameter using empirical models derived from height measurements has been shown to be inadequate in many cases (see Figure 76), leading to poor valuations.

Recent research to address this challenge involves the use of terrestrial LiDAR scanners to measure tree dimensions below the canopy. This approach, however, requires a considerable amount of time by a human operator. The use of terrestrial LiDAR has not yet proven economical, and a more efficient method is desired.

Figure 76 - New Zealand Pine Plantation Exam

7.2.2 Concept Description

General Description

The proposed system involves a small mobile platform, such as a small quadrotor, and lightweight sensor system, configured to measure the most important metrics only. The system is best suited to easy–to–navigate forest, such as organized tree plantations or widely spaced forests.

Whilst terrestrial LiDAR systems are capable of determining tree measurements to incredible precision, they are too heavy (greater than 5 kilograms), too slow (5 minutes per scan), and too power–demanding (40–80 Watts draw at 19 Volts) to make mobile with current technologies[104]. Furthermore, only a small portion of the information collected by terrestrial laser delivers the majority of the practical value. Therefore, we propose using an alternative sensing method described in Section 7.2.5.

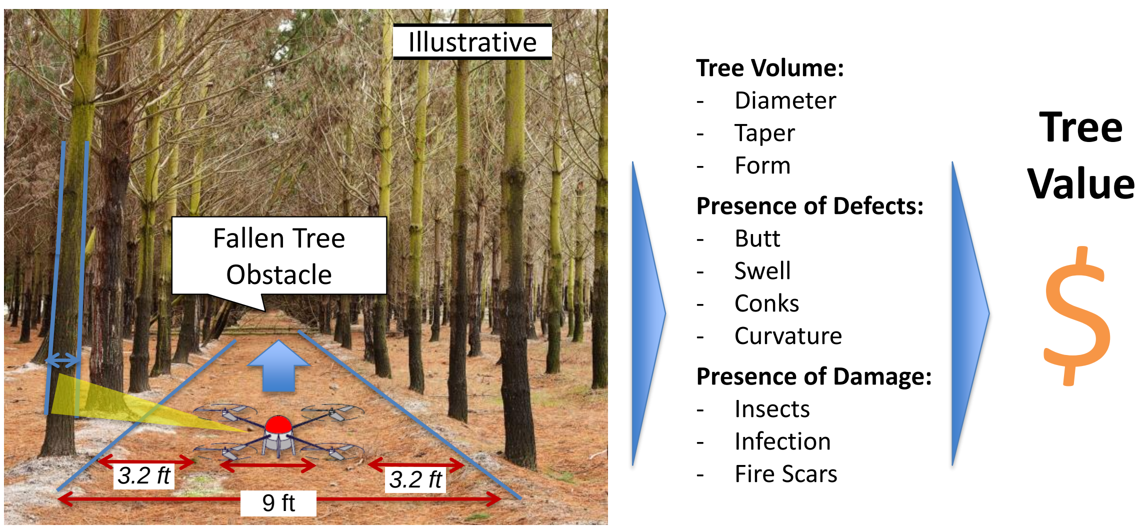


Figure 77 – Example Tree Plantation and Factors that Impact Tree Value

7.2.3 Needs Analysis

Overarching Need: The system is required to reduce the cost and increase the efficiency of conducting a ground based timber inventory/timber cruise.

- *Capability*: The system should reduce the number of foresters required to conduct an inventory/timber cruise by reducing the time required per forester to survey a unit area.
- *Capability*: The system should enable a potential increase in the survivable area by exhibiting sufficient endurance and range.

- *Capability*: The survey data quality must be equal to, or greater than, data from existing manual methods (note that data collection does not need to be as detailed as a terrestrial scanner).
- *Capability*: The system needs to be able to measure the most important tree parameters, such as diameter, taper, and form.
- *Capability*: The system will, ideally, capture information on additional factors related to timber value, such as the presence of defects, presence of disease or insect damage and presence of fire damage.
- *Adaptability*: The system needs to be sufficiently transportable between forests.
- *Adaptability:* The platform and sensors need to be adaptable to a range of commercial forest types categorized by different tree species, tree spacing and different terrains.
- *Reliability/Survivability*: The system needs to be reliable when faced with a range of weather conditions and forest types. For example the system needs to remain reliable in partially GPS–denied environments due to dense canopy cover.
- *Maintainability*: The system needs to be easily maintained.
- *Affordability*: The system needs to be cost effective with respect to existing survey methods, including both manual inventory methods and terrestrial LiDAR inventory methods.

7.2.4 Functional Requirements

There are a number of functional requirements for the proposed system. For brevity, we list only the most important requirements here.

Ability to Navigate Multiple Forest Types

To navigate autonomously through a cluttered and unstructured forest environment, the UAS will require the following capabilities:

- The system is required to autonomously navigate the forest environment:
    - The system is required to detect obstacles within the flight path: trees, branches, bushes, people and other potential obstacles.
    - The system is required to generate a path to navigate around immediate obstacles.
    - The UAS trajectory should remain centered between trees.
    - The system is required to monitor power levels and system health, and automatically return to a control station for charging or maintenance as required.

- o The system is required to have a human interface for downloading survey instructions.

Ability to Measure Trees Parameters

- The system is required to generate 3–dimensional measurements of diameter at a number of heights on the tree.
- The system is required to store the data onboard the mobile platform for later download and processing.

7.2.5 Description of System Elements

Choice of Platform

The system's capabilities are heavily dependent on the choice of mobile platform. Smaller platforms are more constrained by payload size and flight time endurance. Larger platforms are constrained by tree spacing in dense forest environments. Ideally, the proposed mobile platform will navigate effectively in most forest plantations and some naturally regenerated forests.

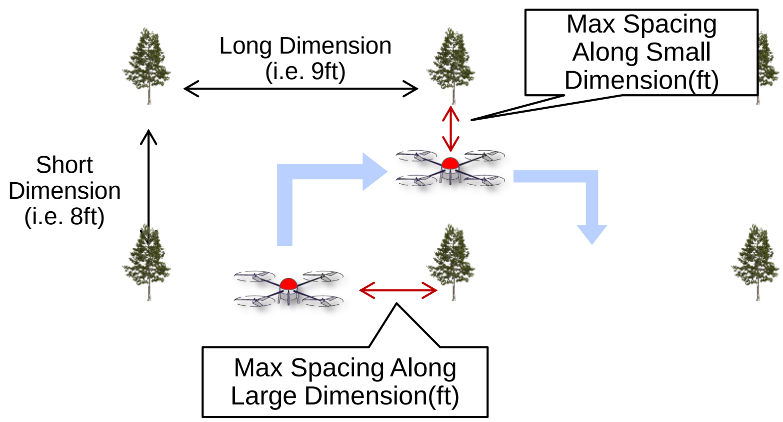


Figure 78 - Definition of Forest Plantation Dimensions

To determine plausible platform dimensions, we first examine plantations configured in rows of trees. Such plantations are characterized by a long dimension and short dimension (Figure 78). Ideally a mobile platform will be able to navigate through both forest dimensions whilst leaving sufficient spacing between the platform and trees such as to avoid unintentional damage from branches.

Table 6 illustrates the set of plantation configurations found in the United States. The baseline configuration used for this analysis assumes a forest spacing of 9 feet by 8 feet. This dimension is relatively common based on forestry literature. What can be gleaned from Table 6 is that a small quadrotor platform of roughly 2.6 feet in width may operate with sufficient spacing in most common plantation configurations. Any larger, however, will reduce the platform's adaptability.

Table 6 – Common Forest Plantation Tree Spacing

Width of quadrotor	2.62	ft
min distance to tree	2.5	ft
Max spacing small dimension	1.5	ft
Max spacing large dimension	2.5	ft

True = Platform will fit along either forest dimension
False = Platform will fit only along long dimension
False = Platform will fit along neither dimension

Spacing (feet)	*Trees per acre*	*Max Spacing Along Small Dimension(ft)*	*Max SpacingAlong Large Dimension(ft)*	*Navigatable Forest Type?*	
5x5	1,742	1.2	1.2	FALSE	
5x10	871	1.2	3.7	FALSE	
6x6	1,210	1.7	1.7	FALSE	
6x10	726	1.7	3.7	TRUE	*Common dimensions*
7x7	889	2.2	2.2	FALSE	
7x10	622	2.2	3.7	TRUE	
8x8	681	2.7	2.7	TRUE	
8x10	545	2.7	3.7	TRUE	
8x9	**605**	**2.7**	**3.2**	**TRUE**	Baseline Dimension
6x12	605	1.7	4.7	TRUE	
4x18	605	0.7	7.7	FALSE	
3x24	605	0.2	10.7	FALSE	

Most micro quadrotor UAS platforms fall into three size categories as illustrated to scale in Figure 79. A review of current, commercially available, high performance brushless quadrotors suggests that only the smallest category will fit comfortably within most plantation configurations. This smallest size category will leave a spacing of approximately 3.2 feet between the vehicle's rotors and each tree, or approximately 1.2 feet between the vehicle's rotors and extended branches. Based on literature, tree branches may extend roughly 2 feet at a height less than breast height common pine plantations.

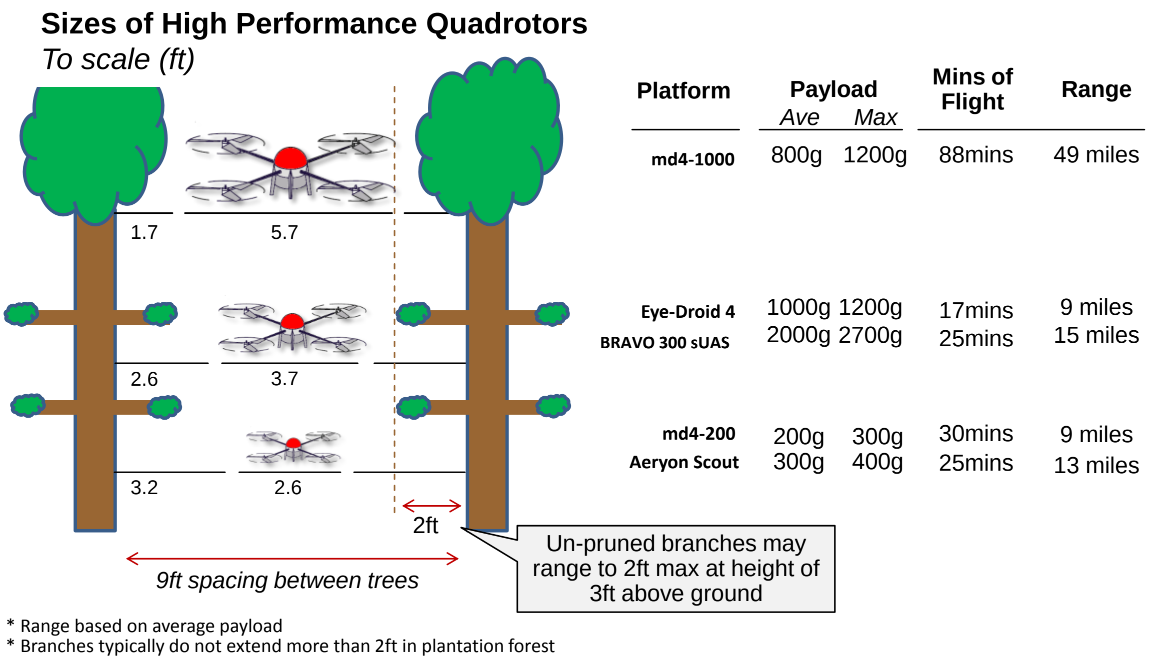


Figure 79 – Selection of High Performance Quadrotors

The necessity to use the smallest category quadrotor significantly limits the capabilities of the system. For example, platforms such as the md4–200 by Micro Drones or the Aeryon Scout by Aeryon Labs have a maximum payload capacity of only 300–400 grams and maximum range of approximately 9–13 miles. Assuming a sensor can be designed to meet the payload requirement, and assuming that a quadrotor must travel at a maximum of 25 per cent of the nominal vehicle speed in order to avoid collisions and simultaneously measure trees, we estimate that approximately 3000 trees could be measured per battery charge. This figure is a rough estimate only and requires experimental verification. This figure could be increased by sing an autonomous battery change out–station, such as the system described in Section 5.2.

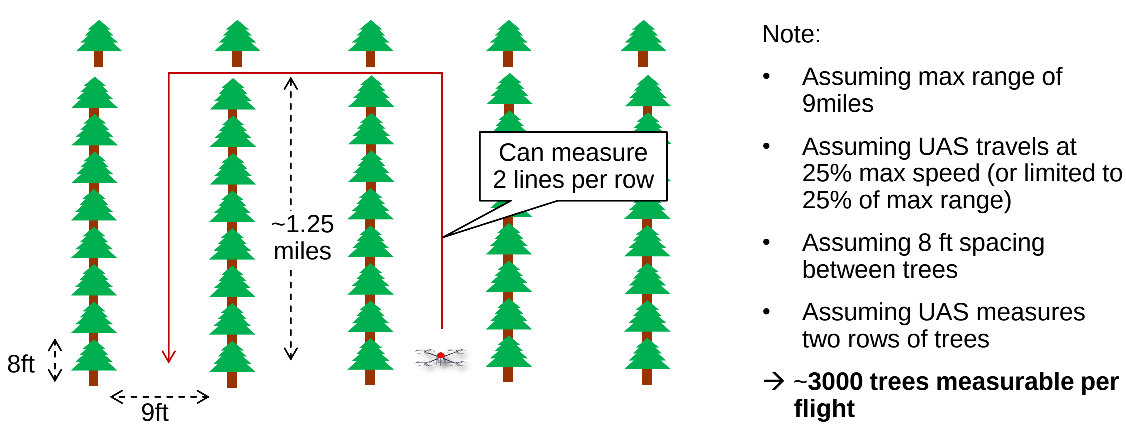


Figure 80 – Estimate for Trees Measured per Flight Charge

Choice of Sensor

Based on the above analysis of feasible platform options, we are left with an important question: Can we find an appropriate sensor combination that weighs less than 400 grams and that is capable of measuring tree diameters, taper and tree form? Furthermore, can we use this sensor to assist with navigation and obstacle detection?

Possible sensor candidates include:

- A 2–dimensional digital camera, coupled with low frequency range finder (sonar or small LiDAR);
- A higher frequency micro LiDAR;
- A time of flight camera or stereoscopic camera;

<u>Option 1 – A 2–dimensional digital camera coupled with low frequency range finder</u>

The first sensor possibility includes a digital camera to detect obstacles, center the vehicle amongst trees and take high resolution photographs. A selection of lightweight cameras for use with small quadrotors is shown in Figure 81.

Accurate measurements of each tree can be generated from 2–dimensional photographs if the distance to each tree is known at the time of the photograph. Distance can be measured using either a sonar sensor or ultra–lightweight, low power LiDAR. For example, the Hokuyo URG–04LX LiDAR sensor weighs only 160 grams (Figure 82). This sensor has a range of 5 meters only. When coupled with the Point Grey camera of Figure 81, the sensor combination totals only 200 grams, which falls within the required payload capacity, assuming an additional sensor frame is required.

Measurements can be determined in post processing from the raw sensor data using the following steps:

1. Edge detection software is applied to the photographs to detect tree edges.
2. The distance to each tree is determined by matching photographs with range finder data.
3. By counting the pixels between tree edges as detected by the edge detection algorithm, the actual width (diameter) and other tree measurements may be estimated by transforming pixel width to actual width using the camera calibration properties (the camera matrix).

	Tetracam	Aeryon Labs	PointGrey
	ADC Series - High Quality Visible and NIR Imaging	3 Axis stabilized Visible Imaging	Light Weight Visible Imaging

Weight:	~200 grams	~250 grams	41 grams
Resolution:	3.2 MPs	8 MPs	8 MPs
Spectrum:	NIR and Visible	NIR or Visible	Visible
Stabilized:	No	Yes	No
Power:	NA	NA	2.5W

Figure 81 – Lightweight Camera Options

An additional advantage of using a 2–dimensional, high–resolution camera is that images can be used to detect the presence of defects, disease and insect damage through manual or automated inspection of the photographs.

<u>Option 2 – High Frequency LiDAR</u>

The second sensor option involves the use of slightly more powerful small LiDAR such as a Hokuyo UTM–30LX. This particular sensor weighs 233 grams and thus still falls within the payload limit of 400 grams. This sensor is able to create a relatively accurate 2–dimensional point cloud over a range of 30 meters. If configured to scan in more than one plane, this sensor could, in theory, generate a number of tree measurements, as well as assist with vehicle obstacle avoidance.

<u>Option 3 – Stereoscopic Camera or Time of Flight Camera</u>

The last option includes the use of a time of flight or structured light camera. Time of flight cameras capture depth and color information simultaneously. Stereoscopic cameras are one form of time of flight camera. The smallest time of flight cameras weigh as little as 88 grams (see Figure 83). These cameras have a limited field of view and range; however, given our platform is expected to fly within a few feet of each tree, such a camera may be an effective option. An evaluation of various micro LiDAR and time of flight 3–dimensional camera options can be found in the paper: ‘3D Computer Vision of Wide Scope’[105].

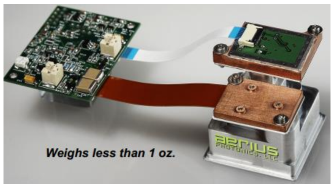
Hokuyo UTM-30LX
Or R314-HOKUYO-LASER4

Weight: 233g
Power: 8.4W
Rate: 25msec/scan (40Hz)
Range: 0cm to 30m
FOV: 240°

Hokuyo URG-04LX-UG01

Weight: 160g
Power: 2.5w
Rate: 100 msec/scan (10.0 Hz)
Range: 0cm to 5m
FOV: 240°

Aerius Photonics
MLR100 of UAS



Weight: 22g
Power: 0.4W
Rate: 4 msec/pulse
Range: 0cm to 100m
FOV: 0°

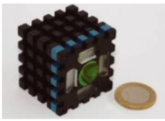
Source:
http://www.acroname.com/robotics/parts/R314-HOKUYO-LASER4.html
http://aeriusphotonics.com/pdf/02_MLR100_Miniature_Laser_Rangefinder_Series_09_2010.pdf

Figure 82 – Lightweight LiDAR Options

Bumblebee FireWire stereo camera

Mass: 342 grams
Range ~2.5m
Power Consumption: ~2.5W
Resolution1032x776 @20fps

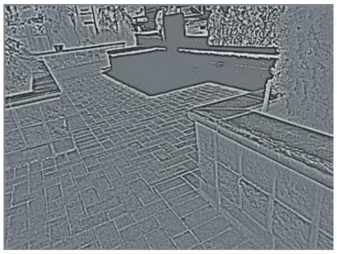
CSEM ARTS 3D Time of Flight camera



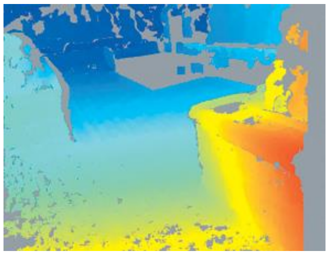
Mass: 88 grams
Range ~1.8m
Power Consumption: ~2.5W
Resolution176x144 @30fps

Rectified Image

Edge Detection Image



Depth Image & Point Cloud



http://www.ptgrey.com/products/triclopsSDK/triclops.pdf
http://www.csem.ch/docs/show.aspx/13068/docname/CSEM_ARTTS_3D_TOF_Camera_DataSheet.pdf

Figure 83 – Time of Flight Cameras

Platform Subsystems:

Supporting both the platform and sensor combination will be a number of subsystems. These systems may include a flight controller, battery pack, specialized brushless motors, branch protectors, system heath management system and a battery recharge/changeover system.

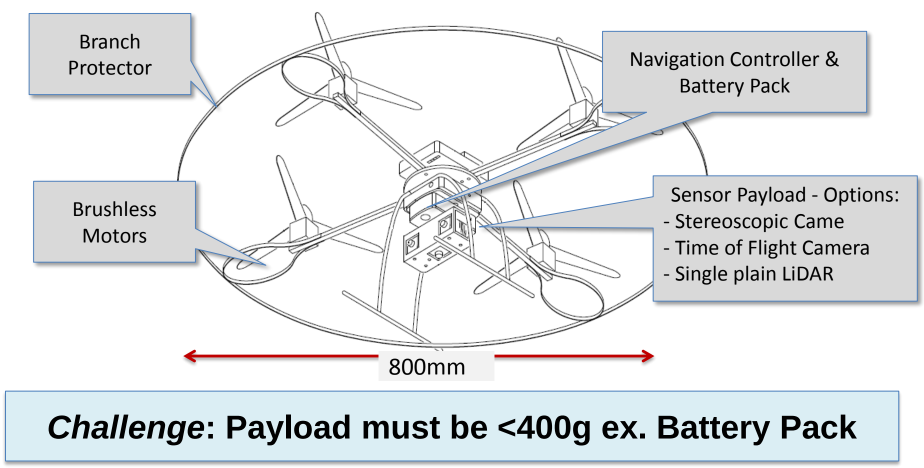


Figure 84 – Proposed Platform System Design

7.2.6 High Level Business Case

Based on a recent study[106], the importance of conducting an accurate timber inventory prior to the sale of timber is clear. The consensus among experts surveyed in the study indicates a minimum attributable value of timber of $300 per acre as pulpwood, with a maximum value of timber of $800 per acre for high quality timber accompanied by a detailed timber survey. Timberland with incomplete inventory information may yield a market price somewhere in between the minimum and maximum.

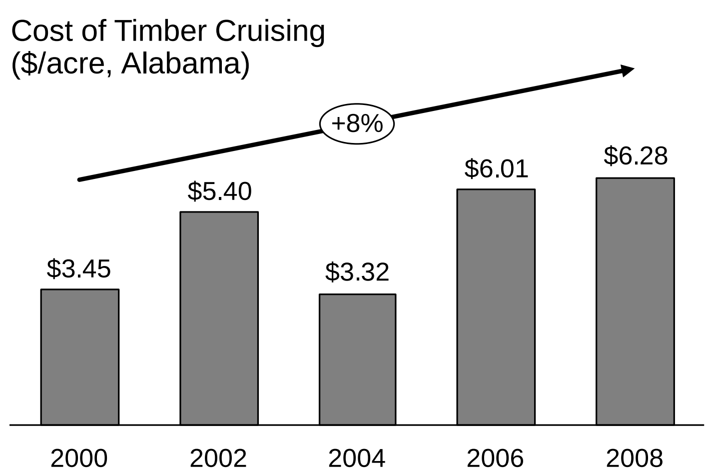


Figure 85 - Average Costs of Timber Cruising

The average cost of timber cruising in the south of the United States was approximately $6.30 per acre in 2008, and growing at roughly 8 per cent compound annual growth rate[107]. Costs are heavily dependent on local availability of foresters, and potential costs associated with travel and lodging to and from the forest sites.

The value proposition for the proposed system is derived from (1) increased ability to survey more area, leading to greater data accuracy and, therefore, greater ability to charge a higher price; and (2) the ability to reduce the number of foresters required to survey a given site, thereby saving on fees, travel and lodging and reducing the survey cost per acre.

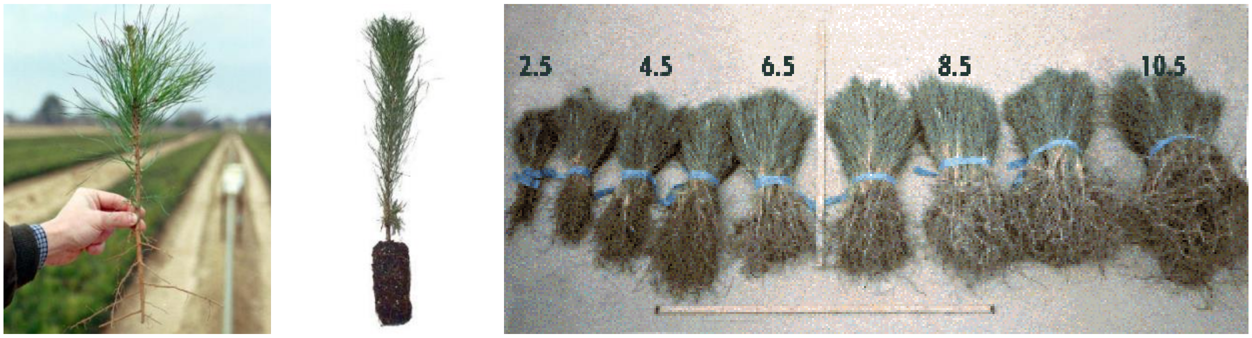
7.3 Concept III: Forest Sensor Deployment and Monitory System

7.3.1 Opportunity Description

There are many factors that contribute to the growth and survival rate of seedlings. Some factors regarding site preparation can be controlled. These factors include control of surrounding vegetation, and use of fertilization. Other weather–related factors are not as easily controlled. These factors include: soil moisture and temperature at time of planting, rainfall, wind, and ultra–hot days directly after planting.

During unfavorable planting conditions, for example low soil moisture or temperature, the survival rate can be improved by using larger, more resilient seedlings, or by using more resilient containerized stock. The use of larger seedlings and/or containerized seedlings, however, increases overall regeneration costs. For example, a standard bare–root seedling may 4 –6 U.S. cents versus 12 – 16 U.S. for a containerized seedlings[108]. That is, more resilient containerized seedlings may cost up to three times as much as standard seedling stock.

Many foresters argue that containerized stock will always be more economical due to the increased resilience against soil conditions and weather. However, many reports indicate that containerized stock does not provide any benefit when soil and weather conditions are favorable[108, 109]. Therefore, by monitoring soil conditions directly prior to planting a new stand, foresters can make more informed decisions regarding the choice of seedling stock and timing of planting activities. Unfortunately, no financially viable system to measure soil properties over vast forested areas yet exists.



Bare–root loblolly pine seedlings | *Containerized stock* | *Seedling size classes Optimum seedlings may have a RCD of 7.5 ,8.5 ,9.5, and 10.5 mm, but may also be more costly.*

Figure 86 – Comparison of Different Seedling Stock Packaging and Classes

7.3.2 Concept Description

The proposed system utilizes low altitude unmanned aerial systems to deploy low cost disposable soil sensors into areas designated for reforestation. At set spatial intervals, such as every 10 miles, the UAS drops a sensor into the field. At these widely spaced intervals, sensors will be unable to communicate via a mesh radio network, making data retrieval a challenge. Closer spaced intervals required for a mesh network increases the cost of the system, as more sensors are required to cover the same forest area.

To solve this challenge, a low cost, unmanned aerial vehicle is configured to fly over the forest at designated dates and time intervals to receive information transmitted from the sensors. At all other times, sensors do not transmit data, so as to preserve power. The deployment and data retrieval process is illustrated in Figure 87.

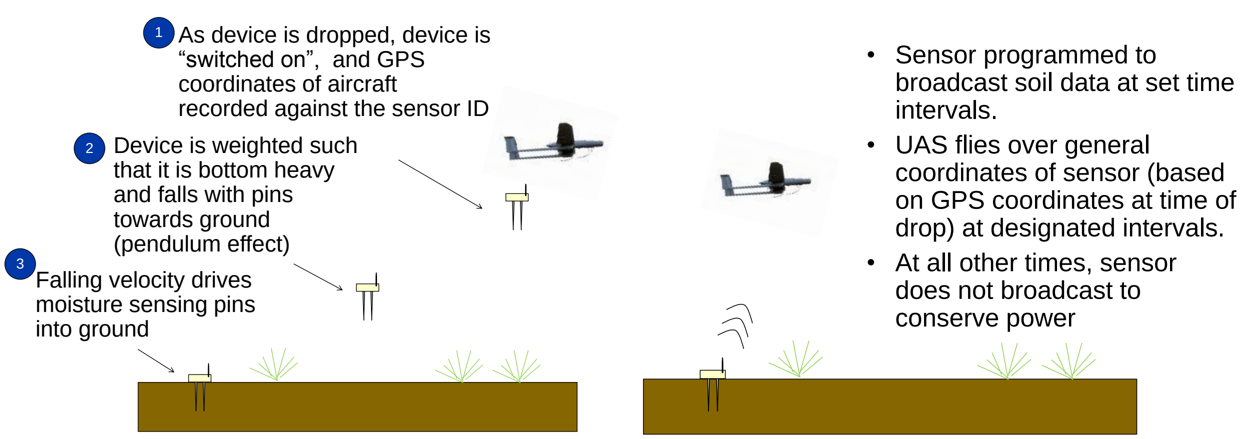


Figure 87 – Illustrative Deployment Strategy and Data Retrieval Strategy for Remote Soil Sensor

The information generated from the sensors may be used under a variety of circumstances. For example, forest managers in North America and Europe often try to plant new timber stands as early as possible in the spring to provide as much time as possible for new seedlings to establish a root system before the hot summer months. If the ground, however, is still not fully thawed, seedlings may suffer frost damage and perish. Temperatures below 32 degrees Fahrenheit will cause water in plant cells to freeze and resultant ice crystals will kill cells by damaging cell membrane systems.

In addition to freezing the seedlings, there is also a risk of exposing seedlings to excessively dry conditions. Foresters are often required to plant later in the spring or out of season as a result of availability of equipment or human resources. Planting later in the season poses a greater risk of loss due to poorer soil moisture conditions.

An illustrative decision making process with available soil data is illustrated in Figure 88. If moisture content is below a set threshold then the forest manager may (a) decide to delay until after a rainfall, (b) use containerized stock to improve survival rate, or (c) delay reforestation to the next season.

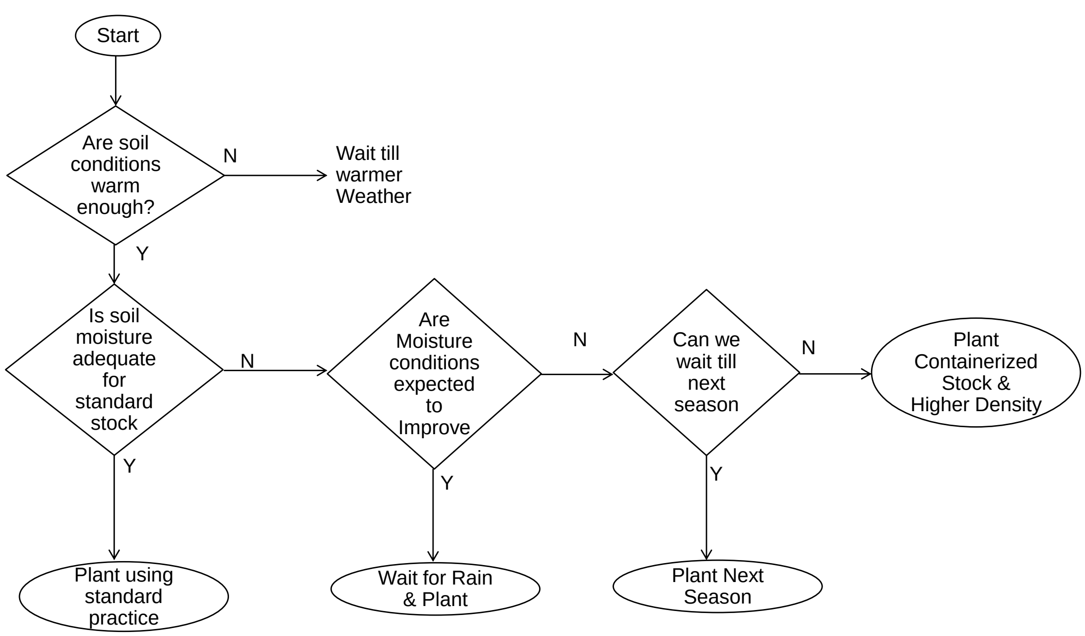


Figure 88 – Reforestation Decision Making Process with Regards to Temperature and Moisture

7.3.3 Needs Analysis

The data needs for the proposed system may be broken down into four categories: What soil parameters must be measured? How accurate and frequent do measurements need to be? Over what sized area does the system need to operate? How long does the system need to last in the field?

- *Capability*: The system must measure soil temperature and soil moisture content at a depth of roughly 10 centimeters below the surface. Surface moisture and temperature can differ significantly with depth due to surface evaporation and warming during the day. Surface measurements can provide misleading results and measurement at a depth of 10 centimeters is deemed a more reliable indicator.
- *Capability*: The systems sensors will ideally measure soil pH, nitrogen and nutrient content in addition to temperature and moisture. These additional measurements are useful, but not system critical and should not come at the expense of increasing the system cost. These soil parameters do not vary significantly over time, and therefore do not require frequent measurement prior to planting a new timber stand.
- *Capability*: The system needs to make soil measurements once or twice per day. Response time for each measurement reading does not need to be fast.
- *Capability*: The accuracy of each sensor, as defined by the error distribution over a set of sensors, may be rough. Accuracy may be obtained by averaging readings over multiple sensors. This is in contrast to most commercially available off–the–shelf moisture sensors, which advertise high precision and rapid response times, but are costly to purchase.
- *Capability:* The system needs to be able to measure soil conditions over potentially vast areas (hundreds of thousands of acres). The spatial granularity of readings, however, can be crude, as soil conditions are relatively consistent over short distances categorized by a few miles.
- *Reliability/Survivability*: At a minimum, the system should have an operational life span of one month. Ideally, the system will operate for up to a year in the field.
- *Reliability/Survivability*: It is desirable that the system/sensors leave no environmental impact.
- *Affordability*: The benefits from increased seedling yield rate and optimized seedling costs must outweigh the cost of the system, including sensor costs and UAS system costs.

7.3.4 Functional Requirements

For brevity we list only the most important requirements:

- The system requires a method and apparatus to deploy soil moisture sensors into the field.
  - Each soil moisture sensor must be designed to penetrate into the ground so as to measure soil parameters at a depth of 10cm below the ground surface.
  - Soil sensors are required to be sufficiently durable to survive a deployment drop from above 100 meters.
  - The deployment UAS should be capable of carrying and deploying at least 20 sensors per flight.
  - Required spacing between sensors should be roughly10 square miles per sensor
- The system requires a method and apparatus to retrieve information from deployed soil moisture sensors.
  - The system requires a UAS system equipped with a system to locate individual sensors and wirelessly upload data.
  - Each sensor must have a wireless transmission range of a minimum of 200m such that a temporary yet stable wireless data link can be established with an overflying UAS vehicle.
  - Wireless transmission data rates do not need to be high bandwidth and may be as low as 4.8Kbps.
- Each sensor is required to last a minimum of one month in the field and must contain a minimal number of non–biodegradable components
- Moisture readings are required to be accurate to roughly +/– 0.05 ft^3ft^{-3} over a wide variety of soil types. Calibration of the soil moisture sensors to the particular soil type is permitted.
- Temperature readings should be accurate to +/– 2 degrees Fahrenheit.
- There is no requirement placed on sensor response times.

7.3.5 Description of System Elements

UAS Platform for Sensor Deployment:

A small to medium sized UAS platform is proposed to carry and deploy a payload of lightweight sensors. If each sensor weighs approximately 200 grams, then a payload of 25 sensors will weigh 5 kilograms. This is roughly the payload capacity of the High Performance Photomapping UAS reviewed in Figure 38 of Section 5.1. Ideally, the same small profile UAS platform would be used for both sensor deployment and data retrieval.

Sensor Design:

There are a number of options with regard to potential moisture and temperature sensor designs. For example, there are benefits to both a low cost disposable sensor design, and higher cost recoverable design. Based on interviews, both options may be viable, depending on the particular geographic conditions and specific needs of the forest manager.

The components of an illustrative low cost disposable design are detailed in Figure 89. The important components include: the RF transmitter, the moisture and temperature sensors, the microcontroller and the casing. For a disposable sensor design to be financially viable, each sensor must cost less than a few dollars.

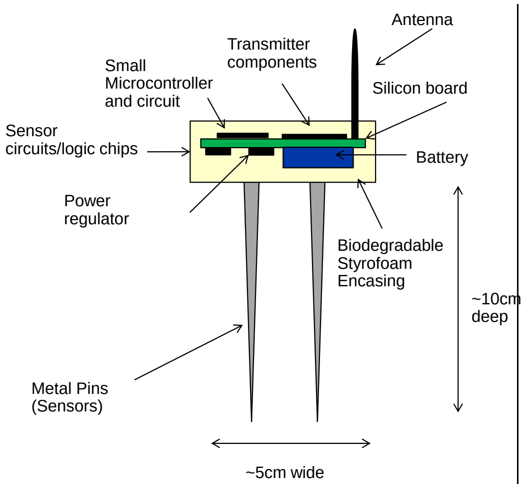


Figure 89 – Disposable Soil Moisture and Temperature Sensor Design

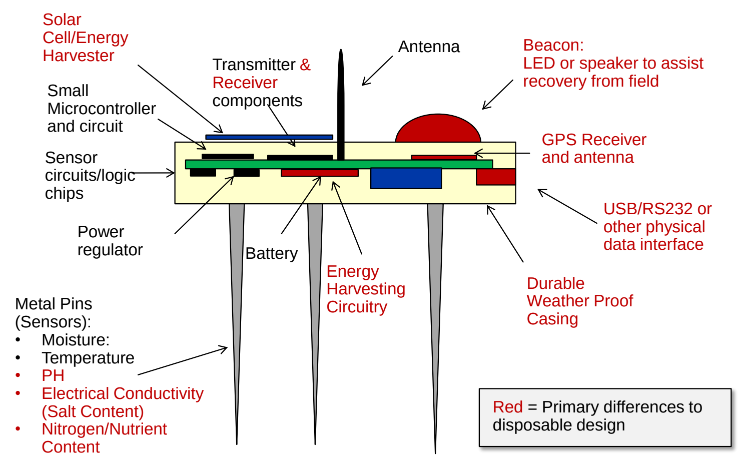


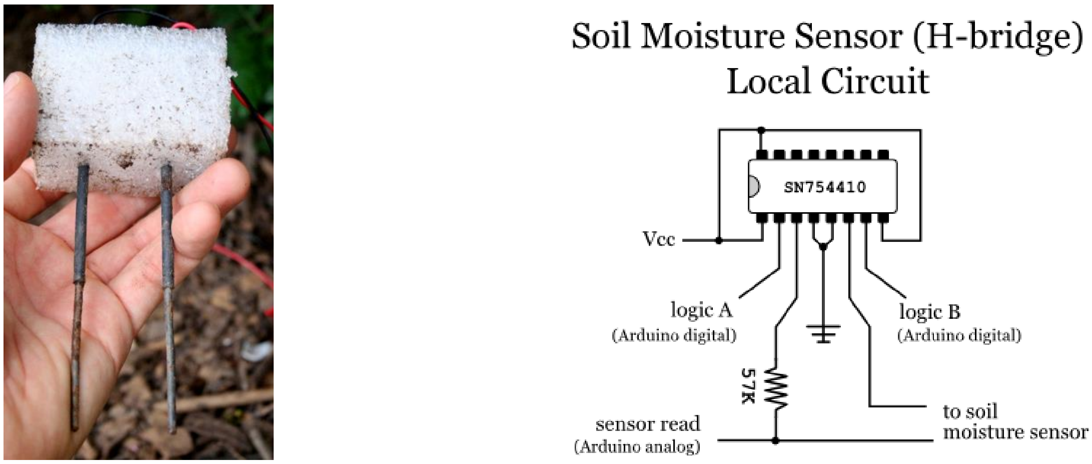
Figure 90 – Durable/Recoverable Soil Moisture and Temperature Sensor Design

A potential recoverable design is illustrated in Figure 90. A recoverable design may include a GPS receiver and locator beacon to assist foresters with locating and recovering sensors from the field. A recoverable system may also include an energy harvesting system, such as a solar cell, to enable operation for greater periods of time. Furthermore, a recoverable version may comprise a more accurate and more durable soil moisture sensor, and additional sensors such as pH and Nitrogen sensors.

Moisture Sensor Mechanism:

Low Cost Options for Disposable Design

A number of soil moisture probe technologies exist; however, most cost upward of $100 per unit (Figure 92). Because moisture probes are so expensive, many gardening blogs describe low cost homemade alternatives that perform well but have poor life span. Figure 91 illustrates a popular ‘home–made’ design made of galvanized steel wire (12 gage or equivalent), a foam block and a single H–bridge integrated circuit chip. The total material cost for this sensor design, excluding a microcontroller, is less than USD$2. A thermal couple wire could be added to the design to measure soil temperature in parallel to soil moisture.



Source: http://gardenbot.org

Figure 91 – Resistive Soil Moisture Sensor Design

This type of moisture probe is known as a resistive probe and works by measuring the soil resistance which varies as a function of moisture content. The downsides to this sensor choice are (1) the probe must be calibrated to the specific soil type, and (2) the probe eventually breaks down due to electrolysis of the wires. Therefore, this soil sensor method is only suited to a low cost disposable sensor design for use in forests where soil mineral content, required for calibration, is known from past surveys.

Moderate Cost Options for Recoverable Sensor Design

For a more durable design, resistive probes are not well suited. Table 7 compares the various moisture sensor technologies and the suitability to the particular forestry challenge. The high frequency capacitive probe was deemed the most suitable choice for a retrievable sensor design. This type of moisture probe is more accurate and more durable than resistive variants, yet more affordable with respect to other moisture sensor technologies. Capacitive probes still retail for more than $100 and therefore, a durable and retrievable sensor design may not be financially viable.

Soil Moisture Probe Options

Two wire home made solution - excludes microcontroller (<$2)

Two wire resistive sensor - excludes microcontroller - equivalent to home made solution ~$10

Gypsum block resistive Moisture Sensor (~$50)

High frequency capacitive soil moisture sensor (~$100)

Integrated contact probe(~$300)

Time domain impedance dielectric reflectometry Probe ($1000 - $2000)

Neutron soil moisture probe (>$5000)

Figure 92 – Soil Moisture Probe Options by Price

Table 7 – Comparison of Soil Moisture Sensor Technologies

	Neutron Moderation	TDR	FD (Capacitance and FDR)	ADR	Phase Transmission	TDT	Gypsum block resistance sensor
Reading range	0-0.60 ft^3ft^{-3}	0.05-0.50 ft^3ft^{-3}or 0.05-Saturation (with soil specific calibration)	0-Saturation	0-Saturation	0.05-0.50 ft^3ft^{-3}	0.05-0.50 ft^3ft^{-3} or 0-0.70 ft^3ft^{-3}Depending on instrument	0-0.60 ft^3ft^{-3}
Accuracy (with soil-specific calibration)	±0.005 ft^3ft^{-3}	±0.01 ft^3ft^{-3}	±0.01 ft^3ft^{-3}	±0.01-0.05 ft^3ft^{-3}	±0.01 ft^3ft^{-3}	±0.05 ft^3ft^{-3}	±0.01 ft^3ft^{-3}
Measurement volume	Sphere (6-16 in. radius)	about 1.2 in. radius around length of waveguides	Sphere (about 1.6 in. effective radius)	Cylinder (about 1.2 in.)	Cylinder (4-5 gallons)	Cylinder (0.2-1.6 gallons) of 2 in. radius	Sphere (>4 in radius)
Installation method	Access tube	Permanently buried *in situ* or inserted for manual readings	Permanently buried *in situ*or PVC access tube	Permanently buried *in situ*or inserted for manual readings	Permanently buried *in situ*	Permanently buried *in situ*	Permanently buried *in situ*
Logging capability	No	Depending on instrument	Yes	Yes	Yes	Yes	Yes
Affected by salinity	No	High levels	Minimal	No	>3 dS/m	At high levels	>6 dS/m
Soil types not recommended	None	Organic, dense, salt or high clay soils	None	None	None	Organic, dense, salt or high clay soils (depending on instrument)	Sandy ad course soils, avoid swelling soils
Field maintenance	No	No	No	No	No	No	No
Safety hazard	Yes	No	No	No	No	No	No
Application	Irrigation, Research, Consultants	Irrigation, Research, Consultants	Irrigation, Research	Irrigation, Research	Irrigation	Irrigation	Irrigation
Cost (includes reader/logger/ interface if required)	$5,000 -15,000	$400-20,000	$100-3,500	$500-700	$200-400	$400-1,300	50-700
Deployable from Air	×	✓	✓	✓	×	✓	Maybe

Data Transmission Technology

Based on the proposed sensor spacing of roughly one sensor per 10 miles, it is unlikely that a radio mesh network will be a viable data recovery option. Mesh networks require significantly closer spacing such that each sensor can communicate with at least one other sensor. Furthermore, data recovery via the cellular network is limited to only those forests near to population centers. Satellite data connectivity via the meridian satellite network is cost prohibitive for this particular application.

Instead, the proposed design utilizes a low cost UAS to retrieve data from the sensors on designated dates and times. Each sensor is to be equipped with a relatively long range, low cost RF transmitter. Transmitters such as the 433Mhz RF Long Distance Transmitter of Figure 93 have a transmission range of greater than 2km and a bulk manufacturing cost of less than $2. An aircraft flying at an altitude of roughly 1000ft could fly over each device to retrieve data with relative ease.

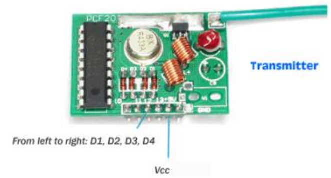


Figure 93 - RF Long Distance Transmitter

Energy Management Technologies

Both a durable and disposable sensor design will require ultra–low power components and potentially a energy harvesting system for extended periods of operation. When utilizing an energy harvesting system, super–capacitors and thin film solid state batteries have many advantages over traditional batteries. Communications protocols such as the ZigBee standard are particularly well suited for low power remote sensing applications. Furthermore, Texas Instruments-designed ultra–low power microcontrollers for use with low power energy harvesting systems are particularly suited to this application.

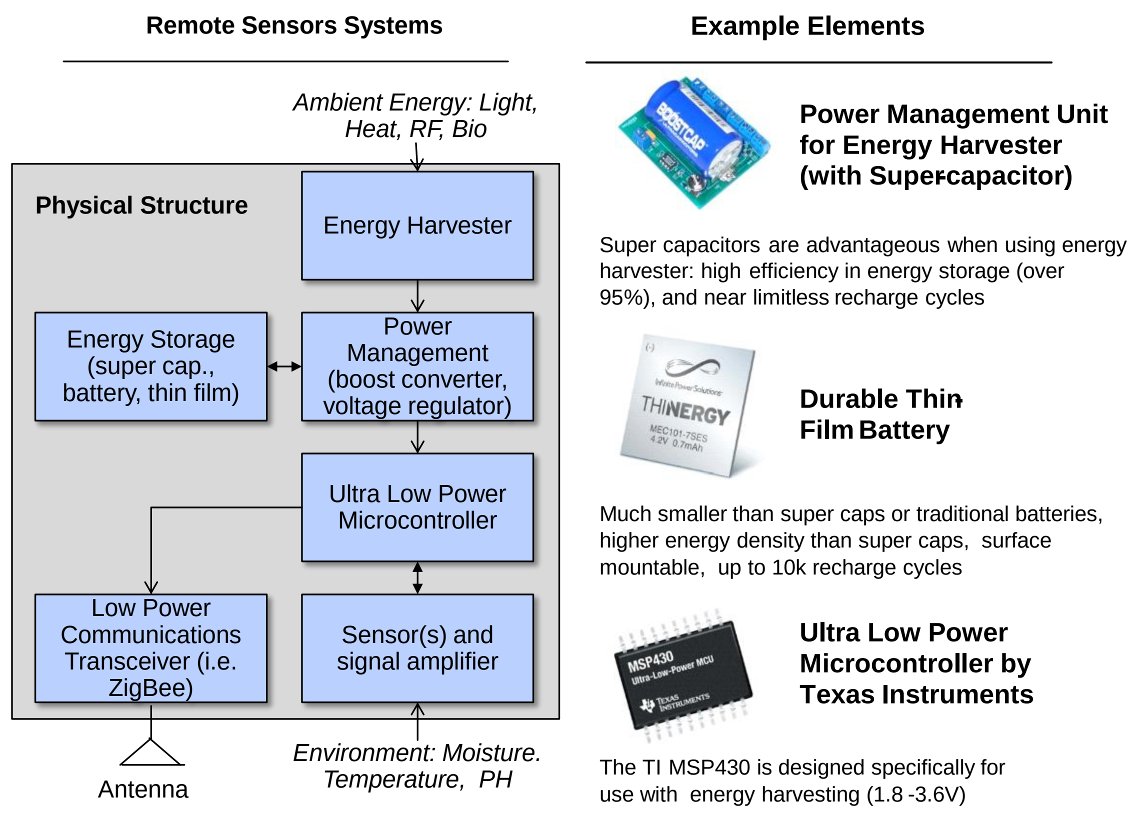


Figure 94 – Power and Communications Architecture Low Power Soil Sensor Design

Biodegradable Design

The proposed system uses biodegradable materials wherever possible to minimize environmental impact. Ideally the sensors will leave no environmental impact; however, electronic circuits, including silicon wafers and ceramic chips are not yet biodegradable.

7.3.6 High Level Business Case

The target market for the proposed forest sensor deployment system is the primary forestry industry. Roughly 2.5 million acres of new primary industry commercial forest is planted in the US per year. This figure is based on 70 million acres of primary commercial forest (Figure 22), and an average new forest turnover rate of roughly 30 years.

The seedling and planting costs account for roughly $67/acre or 17 per cent of primary forest management costs, excluding final logging costs and additional costs associated with monitoring (Figure 95). Planting costs include the cost of seedlings, the cost of physically planting and the costs of replacement of seedling losses.

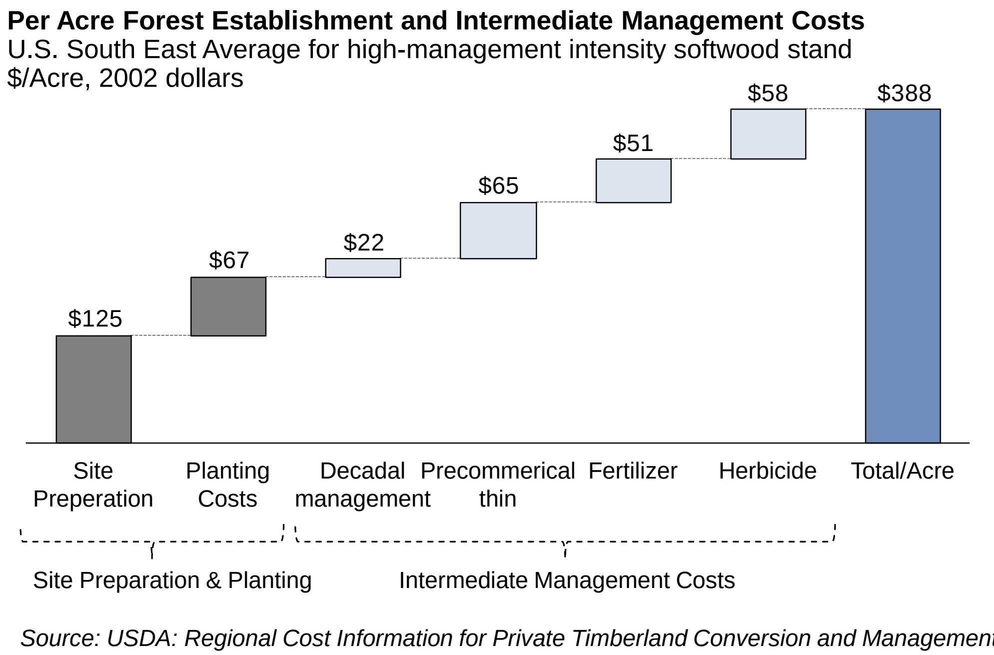


Figure 95 – Forest Establishment Costs vs. Intermediate Stand Management Costs[110]

Planting costs have been known to vary considerably based on year, season and geographic regions. Figure 96 illustrates basic variation of planting costs based on differences in geographic area. The variation in planting costs, whilst not fully understood, is largely driven by choice of seedling stock, containerized versus bare root seedlings, local supply and demand for seedlings, and losses due to poor soil conditions[110]. Thus, knowledge of soil conditions prior to planting could partly reduce the observed variability in planting costs, leading to significant savings for the forest manager.

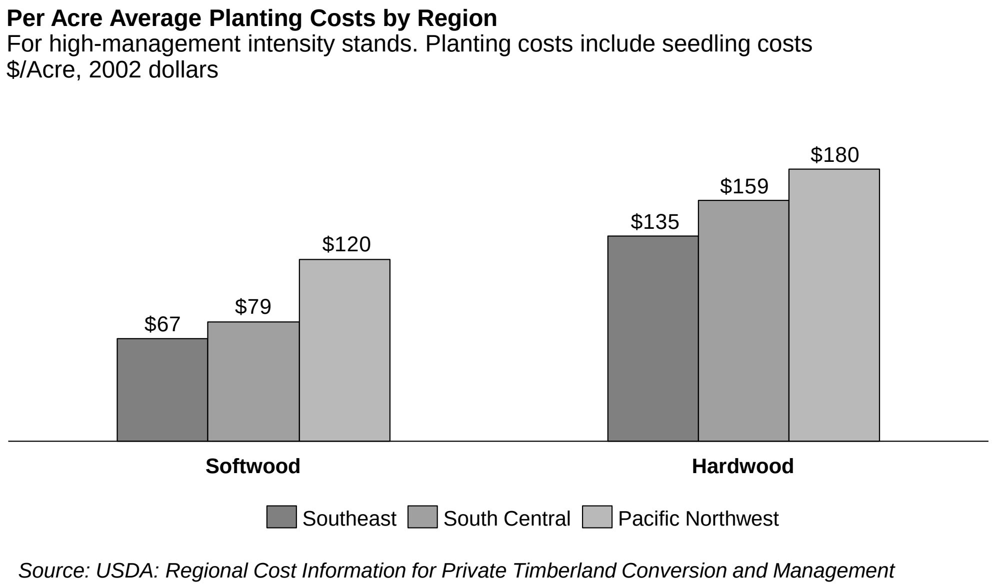


Figure 96 – Observed Variation in Seedling Planting Costs by Region[110]

8 Summary and Key Findings and Conclusions

8.1 Reflection on Frameworks and Methods

This thesis was intended to be broad in nature and to be used to explore the intersection of Product Design Theory, Autonomous Systems Research, and Forestry Science. By evaluating the latest methods and technologies in each of these interdisciplinary fields, we were able to identify a wide variety of market opportunities that could benefit from innovation using autonomous systems technologies. Furthermore, we developed a better understanding of how autonomous systems may be applied to real–world civilian and commercial challenges.

In Chapter 2, we reviewed product design frameworks useful to guiding this work. The general design framework of K.T. Ulrich and S.D. Eppinger[10] was found to be a suitable initial development framework for autonomous systems. Other frameworks such as the UAS development framework by R. Austin [11], whilst useful in their own right, were deemed too specific for this work.

In Chapter 2 we also evaluated applicable design tradeoffs frameworks to understand the tradeoffs between design utility, project cost, project risk, and automation. The multi–attribute tradespace design trade–off method was identified as a leading framework and methodology when developing autonomous systems. We identified a gap in literature, however, with respect to understanding design tradeoffs between system automation and autonomy and system design utility and risk. We proposed that to adequately evaluate the costs and risks associated with increasing system automation, one must consider the implications to four sub–components of automation: path planning, path execution, localization and map building, and sensor information extraction and interpretations.

In Chapter 3, we developed a project charter to narrow the scope of investigation and idea generation. We applied four filters: Which industry? Which customer segment? Which problem or customer activity? Subject to what project constraints?

Chapter 4 developed background theory into forestry science and the forestry management industry. Research conducted in Chapter 4 was used as a foundation for the opportunity identification workshops. In particular, industry structure, industry trends, important stakeholders and current technology trends were reviewed. These four areas of background research proved to be a sufficient theory base from which to launch opportunity identification and concept development workshops.

Chapter 5 developed the background theory required to understand the nascent civilian and commercial autonomous systems market. Industry structure, technology trends and industry regulation were reviewed in the context of understanding available or upcoming state–of–the–art technologies and research.

Chapters 6 and 7 followed the concept development framework developed by K.T. Ulrich and S.D. Eppinger[10] to identify market opportunities and to develop initial feasible system concepts for the top rated opportunities. Market opportunities were evaluated against their overall perceived potential and risk, and the top three opportunities were described in detail in Chapter 7. Chapter 7, in effect, brought together the research from all previous chapters, demonstrating how research at the intersection of the three aforementioned interdisciplinary fields can lead to new and innovative system concepts.

8.2 Recommended Future Areas of Research

This research could progress in any number of areas:

1. The first area of proposed research includes the continued development of the three system concepts described in Chapter 7. In particular, there is still much work to be done to complete the last three steps of the product design framework (Figure 97), including prototype iterations and experimentation, detailed business case development, and detailed system design and refinement.

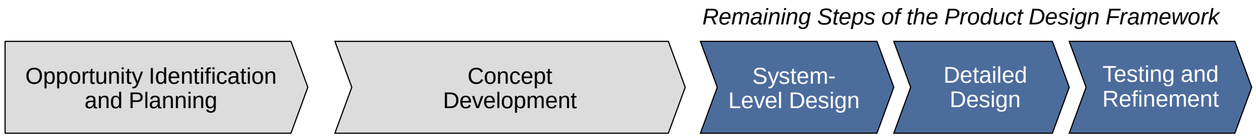


Figure 97 – Remaining Steps of the Product Design Framework

2. The second proposed topic of future research includes revisiting the additional market opportunities identified in Chapter 6 that were not selected for detailed review. Many of these ideas may have real merit and deserve further consideration.
3. The third potential area of additional work includes revisiting the product design tradeoff methods from Chapter 2. In particular, multi–attribute tradespace analysis may be applied to the concept systems of Chapter 7 as part of the design refinement approach.
4. Further, there is opportunity to build upon the multi–attribute tradespace methodology described in Chapter 2. In particular, the approach may be modified to explicitly take into consideration the design tradeoffs between system automation and design utility and risk. Theory regarding design tradeoffs involving automation and autonomy are today considered incomplete by many experts.
5. A final proposed future research area involves expanding the work in this thesis to additional industries. By replacing Chapter 4 of this thesis with a different civilian or commercial industry, more high potential market opportunities may be revealed. Furthermore, by expanding this analysis to a number of industries, a more complete understanding and appreciation for the emerging autonomous systems technologies may be obtained. A better understanding of how autonomous systems may benefit society may attract new technology investors and inform policy makers.

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Glossary of Terms

Autonomous System Related Terms:

LiDAR: LiDAR (Light Detection and Ranging; or Laser Imaging Detection and Ranging) is a technology that determines distance to an object or surface using laser pulses. Like the similar radar technology, which uses radio waves instead of light, the range to an object is determined by measuring the time delay between transmission of a pulse and detection of the reflected signal. "ALSM", standing for "Airborne Laser Swath Mapping," is another name for LiDAR.

T-LiDAR: The "T" in T-LiDAR refers to Terrestrial. A terrestrial LiDAR scanner is a ground based fixed platform scanner commonly used in the mining and construction industry to create detailed three dimensional maps of construction zone or other areas requiring fine measurement.

UAV: Unmanned aerial vehicle commonly known as a drone, is an aircraft without a human pilot on board. Its flight is controlled either autonomously by computers in the vehicle, or under the remote control of a pilot on the ground or in another vehicle.

UAS: The term unmanned aircraft system (UAS) emphasizes the importance of other elements beyond the aircraft itself. A typical UAS consists of the: unmanned aircraft (UAV), control system, such as Ground Control Station (GCS), control link, a specialized data link, and other related support equipment. In practice, the acronym UAV and UAS are often used interchangeably.

M–UAV or M–UAS: The term Micro Unmanned Aerial Vehicle (or System) refers to a class of unmanned corresponding to smaller systems that weigh at most a few kilograms. Most of the UAS systems described in this document are M-UAV class.

VTOL: Vertical take-off and landing (VTOL) aircraft or unmanned aerial system is one that can hover, take off, and land vertically. Both fixed wing and helicopter based vehicles can have VTOL capability.

Quadrotor: A quadrotor is one class of M-UAV that has vertical take-off and landing capability. A quadrotors is characterized by four rotors.

Automation: When defining automation, we refer to the required degree of human supervision or input effort. A system may be described as fully automated when an operator is not required in the decision process, and described as minimally automated when the operator provides most or all of the control input with little to no assistance from the computer controller.

Autonomy: When defining a systems degree of autonomy we refer to the amount of intra–vehicle or intra-agent related automation. The term has meaning only to autonomous systems involving multiple interacting agents, each with its own degree of automation. At the minimum level of network autonomy, there is essentially no collaboration between system agents/nodes. At the maximum network autonomy, agents are in full collaboration and need no human intervention for emergent behavior.

Forestry Related Terms:

FIA: The Forest Inventory and Analysis (FIA) Program of the U.S. Forest Service is a program designed to provide information required to manage public forests in the United States.

USDA: The USDA refers to the U.S. Department of Agriculture, a federal government department that includes the US Forest Services Department.

NFS: National Forest System, federally owned reserves, c.191 million acres (77.4 million hectares), administered by the Forest Service of the U.S. Dept. of Agriculture.

DBH: Diameter at breast height, or DBH, is a standard method of expressing the diameter of the trunk or bole of a standing tree. Tree trunks are measured at the height of an adult's breast, which is defined differently in different countries. In continental Europe, Australia, the UK, and Canada the diameter is measured at 1.3 meters above ground.

Product Design Related Terms:

MVP: In product development, the Minimum Viable Product or MVP is a strategy used for fast and quantitative market testing of a product or product features. A Minimum Viable Product has just those features that allow the product to be deployed, and no more. The product is typically deployed to a subset of possible customers, such as early adopters that are thought to be more forgiving, more likely to give feedback, and able to grasp a product vision from an early prototype or marketing information.

Civilian Market: The civilian market includes non–Department of Defense federal agencies such as the Department of Homeland Securities (DHS) or the US Forest Service. This segment also includes state and local entities, such as regional departments of public safety and municipal police departments.

Commercial Market: The commercial market includes any non–government organizations.

APUC: Average Procurement Unit Cost (APUC) is calculated by dividing total procurement cost by the number of articles to be procured. Total procurement cost includes flyaway, rollaway, sail away cost, including recurring and nonrecurring costs associated with production of the item.

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