System Design for a Rapid Response Autonomous Aerial Surveillance Vehicle

by
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B.S. Mechanical Engineering
The Johns Hopkins University, 1996

Submitted to the Department of Aeronautics and Astronautics in partial fulfillment of the requirements for the degree of

MASTER OF ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May, 1997

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Abstract

The MIT/Draper Technology Development Partnership Project was conceived as a collaborative design and development program between MIT and Draper Laboratory. The overall aims of the two year project were to strengthen ties between the two institutions, to provide students with an opportunity to develop a first-of-a-kind system, and to foster a sense of entrepreneurship in the students working on the project. This first design team consisted of a mix of Master of Engineering and Master of Science students, along with undergraduate research assistants. The team began its work by reviewing the needs of the nation and the capabilities possessed by MIT and Draper which could be leveraged to address those needs. Candidate projects were then developed, and several were further refined through brief market assessments. Based on these assessments, a final project was chosen. The selected project, the Wide Area Surveillance Projectile (WASP), called for the development of a small, unmanned aerial vehicle which could be launched from an artillery gun to provide a rapid-response, time-critical reconnaissance capability for small military units or selected civilian applications.

This thesis reviews the first year of work completed on the project. A systems view is used throughout, describing the top-level trades which were made to develop a product which would meet all of the user's needs. Specific attention is given to the interactions between the various subsystems and how these interactions contributed to the design solution developed by the team. In addition to this chronological description of the project, management lessons learned from the author's experience as project manager are presented, along with recommended approaches for future projects of a similar nature. These lessons may also find applications in the broader realm of rapid-prototyping engineering projects, as well as future projects undertaken as part of the MIT/Draper Technology Development Partnership Project.

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Acknowledgments

First I would like to thank our sponsors at Draper Laboratory. Without their assistance and support, the MIT/Draper Technology Development Partnership Project would never have evolved into the experience it has been. Dr. Byong Ahn, Mr. John Elwell, Dr. Brent Appleby, Dr. David Kang, and Mr. Frank Petkunas have been particularly helpful, and I thank them for their time and effort.

I am also indebted to my thesis advisors, Mr. Charlie Boppe and Dr. Stan Weiss. Both have taught me about the art of systems thinking, and it is an art which I hope to practice for the rest of my life.

A design team is nothing without the spirit and cooperation of group work, and I thank my teammates for a wonderful experience: My MEng classmates, Matt Burba, Ted Conklin, Cory Hallam, and David Iranzo; Tan Trinh; Vlad Gavrilets (for trying to teach a very mechanical mechanical engineer the finer points of GPS systems operation and integration); Bernard Asare; Margarita Brito; Staci Jenkins; and Craig White.

Finally, my thanks to my family, Ritu, Mom, Pop, and Jesse, for their unfailing support and encouragement for all of my endeavors.

Table of Contents

List of Figures

List of Tables

1. Introduction

1.1 Background of the MIT/Draper Technology Development Partnership Project and Thesis Overview

This thesis presents a summary of the first year of work completed for the MIT/Draper Technology Development Partnership Project. The overall aims of this two year program were to strengthen ties between MIT and Draper Laboratory, to provide students with an opportunity to develop an innovative, first-of-a-kind product or system, and to foster a sense of entrepreneuralism in the students working on the project. In addition, at the conclusion of the second year, the design team is to construct a system prototype capable of demonstrating the major features of the product the team will have developed.

The design team began its work by reviewing the needs of the nation and the capabilities possessed by MIT, Lincoln Laboratory, and Draper Laboratory which could be used to address these needs. Initial project concepts were then developed, and a market assessment was completed for each one. Based on the recommendations of the design team, members of Draper Laboratory then selected a final project for the design team to pursue in greater depth. The first year's effort culminated in the development of a preliminary design for the selected system, a gun-launched autonomous aerial reconnaissance vehicle which has become known as the Wide Area Surveillance Projectile (WASP). Subsequent work to be completed next year will move from this preliminary design phase into detail design and ultimately to the construction and testing of the systems prototype.

The efforts of the design team during the first year of the project will be reviewed chronologically in this thesis. Since the author served as the project manager for the program during the second half of the year (the time in which most of the preliminary design work was completed), much of this thesis will describe the project from a "top-level," systems perspective. In particular, the author was responsible for ensuring that the WASP design met all of its requirements, both in terms of technical performance requirements and in terms of schedule and programmatic requirements. A particular emphasis will be placed, therefore, on the interaction between subsystem design work, and the trade-offs that had to be made to develop a system which would meet the requirements set for it. Where appropriate, details of particular subsystems or design elements will be presented. The reader, however, is referred to the other theses[1] completed at the end of the first year of the project for more detailed descriptions of subsystem development work. Together with the overview and connectivity provided by this thesis, these works will provide the reader with a detailed understanding of the methods, techniques, and processes used by the design team to accomplish its mission.

1.2 Project Overview

The design team itself was organized in a novel fashion. Since the team relied primarily on Masters of Engineering (MEng) students for the systems design and development aspects of the project, and because the MEng degree program lasts for only one year, two classes of MEng students would participate in the project. The first group of students would be responsible for defining the project at the highest level, and then for progressing into the preliminary design of the demonstration system. The second class of MEng students would then be responsible for the detail design of the demonstration system, its construction, and testing. Complementing the systems design work of the MEng students, several Master of Science (SM) students would also participate in the project. Together with their faculty advisors, these students would be responsible for the development of new technologies critical to the system's design and functioning.

From the beginning of the project, several overall goals were established for the design effort:

- The product must be a first-of-a-kind system;
- The product must address a national need;
- The product should be considered "high-risk," i.e., have some element of "unobtainium;"
- An integrated, multi-disciplinary approach should be used in the design process;
- The product should merge existing enabling technologies;
- The product should be viable in both commercial and military markets;
- The product should be aligned with MIT, Draper, and Lincoln Laboratory

[1] Matthew Burba, *System Design and Communication Subsystem of an Innovative Projectile*, Cambridge: MIT Press, 1997; Theodore Conklin, *MIT/Draper Technology Development Partnership Project: Systems Analysis and On-Station Propulsion Subsystem*, Cambridge: MIT Press, 1997; Cory Hallum, *MIT/Draper Technology Development Partnership Project: Aerodeceleration, Structures, and System Design of a High-G Rapid Response, Deployable Unmanned Aerial Vehicle*, Cambridge: MIT Press, 1997; and David Iranzo-Grues, *Rapid Response Surveillance System Design and Aerodynamic Modeling*, Cambridge: MIT Press, 1997.

capabilities.

Taken together, these goals meant that the design team had to develop the concept for a new product that would leverage the unique capabilities of MIT and Draper to gain a competitive advantage in the chosen market.

To accomplish its goals, the team followed a top-level master plan, illustrated in Figure 1.1. As shown in this plan, the first step in the process (after approval of the process proposal) was to assess the needs of the nation and to assess the capabilities and facilities which MIT and Draper could leverage to help meet those needs. Based on the combined results of those assessments, the team then developed a list of possible projects, or "opportunities," which could be pursued. After some initial concept development, a market assessment was conducted for the most promising potential projects. The results of this assessment were then used to select a final project for further development. Preliminary design work was then completed, which lead to a risk assessment and mitigation plan and plans for adoption, adaption, and invention. The project will then move into detailed system development, and, finally, the construction of the prototype system.

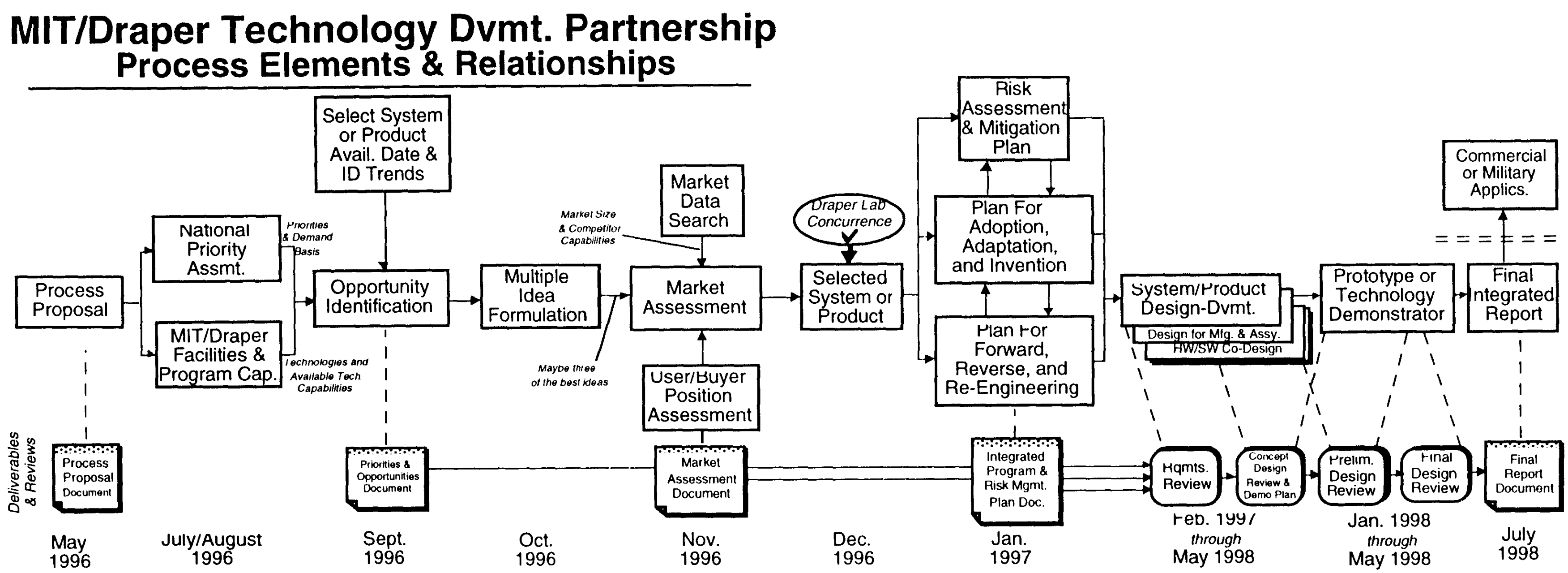

Figure 1.1 Project Master Plan

1.3 Thesis Objectives and Outline

Two objectives are to be met by this thesis. The first is to provide a description of the work completed by the design team and to detail some of the technical highlights of that design. The second objective of this thesis is to provide a model for the design and development process for a time-constrained, rapid-prototyping engineering project. Due to the unique teaming arrangement of this project and the unprecedented nature of the product, this first design team had to synthesize a model upon which to base its activities. By presenting a top-level view of the project, this work will highlight the major milestones in the design process, and the specific steps taken to meet these milestones. It is intended that this thesis will provide a clear understanding of how the project progressed and based on that understanding, the reader should be able to use the methods presented here to develop a product for a similar set of criteria.

To that end, the thesis is arranged in chronological order, each chapter presenting a specific step or related series of steps in the design process. An interaction diagram is presented at the beginning of each chapter, illustrating the milestones specific to the design process described in the chapter. Taken as a whole, these interaction diagrams could be used to develop a master plan for similar projects.

The thesis concludes with a description of the management lessons learned from the project, which might also prove useful to someone planning a similar endeavor, along with recommendations for work which needs to be completed for the present design. A variety of appendices are included. These detail work related to the project which is not directly relevant to the major themes of this thesis.

2. Background Research and Concept Development

2.1 Overview

	Assess National Needs	Assess MIT/Draper Capabilities	Brainstorm Project Concepts	Derive Major Opportunities List	Narrow Opportunities List	Develop Opportunity Areas	Brainstorm Specific Concepts	Select 5 Concepts	Conduct Market Assessment	Project Downselect
Assess National Needs			x	x	x			x		x
Assess MIT/Draper Capabilities			x		x			x		x
Brainstorm Project Concepts				x						
Derive Major Opportunities List					x					
Narrow Opportunities List						x				
Develop Opportunity Areas							x			
Brainstorm Specific Concepts								x		
Select 5 Concepts									x	
Conduct Market Assessment										x
Project Downselect										

Figure 2.1 Background Research and Concept Development Interaction Diagram

The interaction diagram for the first portion of the project is shown in Figure 2.1. As shown, the first step in the project was to assess the national needs and the capabilities possessed by MIT and Draper to meet those needs. Once these assessments had been completed, the team began to brainstorm potential projects, using the results of the assessments as broad guidelines to aide in generating concepts. From this list of potential projects, the team developed several opportunities, which were specific or very broad in nature. These opportunities were then mapped to the national needs, to determine which of the concepts actually met an established need.

The concepts were narrowed, and then aggregated into broader "opportunity areas." Based upon feedback from Draper personnel, the team then investigated several of these areas in greater detail. A second round of brainstorming was conducted to identify specific projects which the team could pursue. These projects were then narrowed to five candidates, which were then further developed. Simultaneously, market assessments were conducted for these projects. Based on the results of these assessments and in conjunction with the recommendation of Draper Labs, a final project was then selected.

2.2 National Needs and MIT/Draper Capabilities

2.2.1 The National Needs Assessment

By contacting a variety of national agencies, a database was developed listing the interests and needs of the nation. Using a document published by the White House, "The National Critical Technologies List,"[2] these needs were categorized into "critical needs bins." These bins, and examples of related technologies are given in Table 2.1. As can be seen from the table, nearly any technology could be categorized into one or several of the bins. This method of organizing the concepts developed by the design team proved both convenient and useful, showing how well the concepts addressed national needs and providing a common basis for comparing potential projects. A project that addressed several bins, for instance, was considered a better one to pursue than one which only addressed one type of need, because such a project would likely appeal to more than one potential market.

Table 2.1 Critical Needs Bins

Energy Efficiency & Independence	Environmental Quality	Information Access & Communication Effectiveness	Health Care & Agricultural Efficiency	Advanced Manufacturing	Improved Materials	Advanced Transportation
• Advanced building systems • Advanced propulsion systems • Storage, distribution, conditioning, & transmission • Advanced energy generation	• Monitoring & assessment • Remediation & restoration • Pollution avoidance & control	• Advanced components • Data & computer routing • Computer interoperability & parallel processing • Information management • Intelligent, complex, adaptive systems • Sensors • Software & toolkits	• Advanced biotechnology • Medical devices & equipment • Agricultural production efficiency • Food supply safety • Advanced human-machine interface	• Robotics & automation • Advanced processes • Semiconductor & microdevice manufacturing	• Alloys, ceramics, composites, etc. • Infrastructure • Stealth • Superconductors • Aircraft structures	• Aircraft & surface vehicle aerodynamics • Advanced avionics & controls • Advanced propulsion & power systems • Systems integration • Advanced human factors & life support

[2] White House, *National Critical Technologies List*, Washington, D.C., March, 1995.

The needs bins also provided a quick reference to the technological priorities of the executive branch of the government. The labels used for each bin gave a clear indication of the overall needs for the country, and served as useful guides during the brainstorming that was to follow.

2.2.2 Assessing MIT and Draper Capabilities

Perhaps even more important than understanding the priorities of the nation, the team also needed to have a clear understanding of the capabilities and facilities available at MIT and Draper Laboratory. It was essential that the project be consistent with these capabilities since the design team would ultimately rely on these capabilities to procure existing subsystems and build the prototype. In addition, one of the goals of the project was to develop a new product which Draper could eventually market.

The capabilities assessment was carried out through a variety of means. Draper's skills were determined based upon a review of summaries and reports from past and present research projects. MIT capabilities were assessed in a similar manner, often complemented by the recruiting material published by individual departments. In addition to the academic MIT engineering departments, MIT's Lincoln Laboratory was also included in the capabilities assessment.

The results of this research were then framed in terms of the national needs bins. As projects were developed and grouped into these bins, the overlap between national needs, MIT/Draper capabilities, and project concepts would become clear. The capabilities assessment lead to the following conclusions:

- Draper's main research areas are focused in the Information Access & Communication Effectiveness and the Advanced Transportation bins. Additional research was also being conducted that related to the Advanced Manufacturing bin, with particular emphasis on micromechanical systems.
- Lincoln Labs skills' reside primarily in the Information Access & Communication Effectiveness arena. Many of their research projects dealt with machine intelligence, adaptive optics, and other advanced sensor systems.
- MIT's skills varied considerably by department. The team focused its assessment on a few, however. Projects in the Department of Aeronautics and Astronautics had a strong inclination toward the Advanced Transportation bin, while the Department of Electrical Engineering and Computer Science had many projects which fell into the Information Access & Communication Effectiveness bin. The Department of Material Science and Engineering was most often linked with the Improved Materials need bin. The Department of Mechanical Engineering had a

variety of projects, some related to Information Access & Communication Effectiveness, others related to Advanced Manufacturing, and still others related to Advanced Transportation. The final department review by the team was the Department of Ocean Engineering, which also had numerous projects related to the Advanced Transportation needs bin.

These results are summarized in Table 2.2. Boldfaced values indicate high scores.

Table 2.2 Percentage of Projects Relating to National Need Bins

	Energy Efficiency & Independence	Environmental Quality	Information Access & Communication Effectiveness	Health Care & Agricultural Efficiency	Advanced Manufacturing	Improved Materials	Advanced Transporation
Draper Laboratories	6.5	3.2	**35.5**	4.9	11.3	4.9	**33.9**
Lincoln Laboratories	0	0	**77.2**	5.3	3.5	0	14
MIT Engr. Depts.							
Aero. & Astro.	2.9	5	**21.6**	11.7	0.7	13.6	**44.5**
EE & CS	12.9	8.1	**54.8**	16.1	8.1	0	0
Mat. Sci. & Eng.	7.5	5	10	7.5	2.5	**57.5**	10
Mech. Eng.	6.2	1.8	**26.7**	11.6	**26**	3.6	**24.1**
Ocean Eng.	7.7	12.8	2.6	0	7.7	0	**69.2**

2.3 Developing Project Concepts

The team began to develop potential project concepts through the use of "freestyle brainstorming." Sitting together as a team, each member was allowed to simply call out any ideas he or she might have. After several sessions working in this manner, the team had generated a substantial list of project concepts covering a very broad range of topics. Some examples included advanced search and rescue systems, cheap cars, improved air traffic control, intelligent transportation systems, advanced systems for water conservation, drug trafficking interception systems, and microsystems with extreme high-g capabilities. Overall, the concepts fell into six categories:

1. Human Aid
2. Transportation
3. Environmental
4. Energy/Power
5. Information
6. Miscellaneous.

The list was narrowed by considering the results of the two assessments which had been conducted. Concepts which addressed national needs and which could be matched to MIT or Draper capabilities were given high scores, while concepts which did not meet those criteria received lower scores.

Systems that received high scores were re-grouped, resulting in four major opportunity areas:

1. Innovative Projectile Systems
2. Intelligent Cooperative Systems
3. Advanced Aircraft Navigation and Control
4. Inexpensive Space Systems,

Using these four subject areas, mini-teams were formed to develop specific project concepts for each area. Each mini-team held several brainstorming sessions to generate an initial list of possible projects. These projects were then narrowed using "back of the napkin" calculations and analysis techniques. Eventually each mini-team began to focus on one or two concepts.

2.4 Moving Toward a Final Project

As the team approached the time at which the market assessments needed to be completed, five projects were selected for further development: an advanced search and rescue system, a hybrid launch system, a reconnaissance projectile system, a solar sail propulsion technology demonstrator, and an autonomous vertical takeoff and landing (VTOL) aircraft.

2.4.1 Autonomous Search and Rescue System (ASARS)

This system was inspired by the apparent need for improved search and rescue capabilities, both for the military and for civilian agencies. The ASARS concept called for the development of a small, autonomous aircraft, several of which could be carried in a transport aircraft such as a C-130 Hercules. In the event of an accident, a transport would be dispatched to the general vicinity. Several of the small autonomous vehicles would then be released to search for survivors. In the event that the accident occurred in the water, the air vehicles were designed to land on the water and then release small, autonomous undersea vehicles to search below the water's surface.

2.4.2 Hybrid Launch System

The hybrid launch system was a concept intended to help lower the cost of placing payloads in orbit. Rather than launching a rocket from the ground, the system used a balloon to carry a rocket to an altitude of 100,000 feet or greater. The rocket was then fired from the balloon, with a significant increase in its performance due to the initial increase in altitude and to the lower air resistance at the higher altitude.

2.4.3 Reconnaissance Projectile System

The basic idea behind this concept was to remove the explosives from an artillery shell and replace them with reconnaissance sensors. Such a sensor-equipped projectile could then be used as a rapid reconnaissance tool to seek out time-critical, high-value targets. The reconnaissance projectile was designed to be disposable, i.e., it would not be recovered after a mission, to help maintain a low unit price.

2.4.4 Solar Sail Propulsion Demonstrator

The concept of solar sails for space propulsion is not a new one. Several enabling technologies, however, have recently been developed which might make such a propulsion both practical and cost-effective. The project proposed by the team, therefore, was to build and fly a solar sail demonstrator to the moon. The author was personally involved in the development of this concept, and the market assessment document and presentation materials for the system are presented in Appendix A.

2.4.5 Autonomous VTOL Aircraft

Another concept which developed from consideration of search-and-rescue problems, this project called for the development of an autonomous aerial vehicle which used a "tail-sitter" configuration to achieve a vertical takeoff and landing capability. The system was intended for a variety of uses, from searching for accident victims to autonomously landing and helping to evacuate victims from the scene of the accident.

2.5 Final Project Selection

All five of the projects described above addressed several of the national need bins and matched well with MIT and Draper capabilities. The final decision as to which project to pursue was ultimately debated among several engineers and department heads of Draper Laboratory. Based upon the results of the market assessment completed for each project, and their own knowledge of Draper's strengths and weaknesses, they selected the *reconnaissance projectile system* for further development.

3. The Systems Engineering Management Plan

3.1 Motivation for the Plan

Once the team had been assigned a project, the next step was to develop a systems engineering management plan (SEMP). This plan was established to guide the detailed engineering work of the project and also help to define the teams deliverables, i.e., the documentation which the team would generate to support its design decisions. The SEMP would also organize the entire engineering process, showing how the results of one large-scale activity flowed into the next.

3.2 The SEMP for WASP

The systems engineering management plan developed for the WASP project is shown in Figure 3.1 and Figure 3.2. As can be seen, the plan covered the time period beginning in January, 1997, through the project's completion in June, 1998. The SEMP, therefore, helped to fill in some of the detailed activities which were not explicitly noted in the project master plan. It also clearly illustrated the roles of the two MEng classes, as conceptual and preliminary design were to be completed by May, 1997, while detail design and prototype construction and demonstration would occur throughout the 1997/1998 academic year.

Following is a description of the major activities shown on the SEMP, as well as their related milestones.

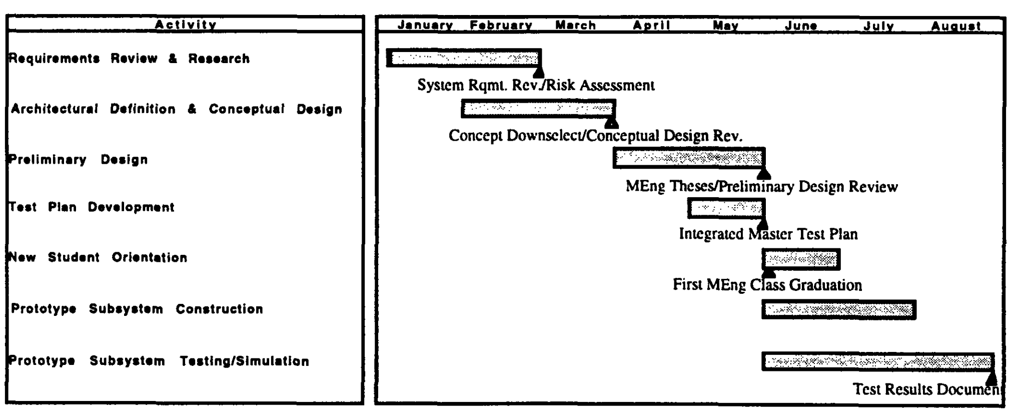

Figure 3.1 Systems Engineering Management Plan -- January - August, 1997

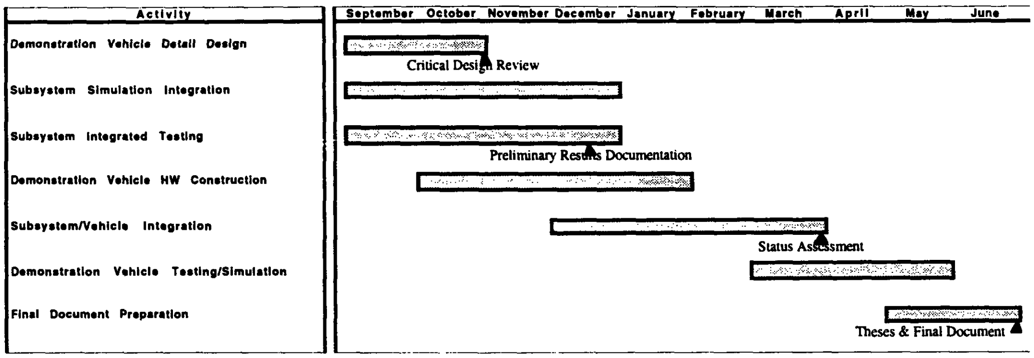

Figure 3.2 Systems Engineering Management Plan -- September, 1997 - June, 1998

3.2.1 Requirements Review and Research

The first step in the design process, the needs assessment and requirements review phase allowed the team to evaluate the customer's requirements and to begin to conceptualize the system. Major activities planned for this period included quality function deployment (QFD) exercises and functional flow analyses. The QFD exercises were the primary tool used by the team to enhance their understanding of the customer's needs and the system's requirements. The QFD allowed the team to both prioritize the customer's needs and to translate the customer's words in detailed engineering requirements and specifications. The functional flow analysis then helped the team to highlight the major functions which the system needed to perform and the sequence in which those functions would need to be performed. This analysis provided the team with the first indication of some the physical systems which might be required to fulfill the WASP design. The functional analysis also generated derived requirements for the system based upon the identified functions.

In addition to development work among the team, this phase also called for external research, contacting the user community to whom the system would be marketed. The team spoke with members of both United States Army and Navy to clarify questions related the system's requirements. It was hoped that these discussions would also reveal any major aspects of the system which the team had overlooked, in terms of needs, operational constraints, or functional definition.

The major milestone planned for this phase of the project was the Systems Requirements Review (SRR), a formal presentation made at Draper Laboratory. During this presentation the team presented the results of its requirements analysis and risk assessment and received approval from Draper for any revisions to the requirements that had been suggested.

3.2.2 Architectural Definition and Conceptual Design

This phase moved the design from the abstract functional analysis to the concrete design of system hardware. Beginning in February and continuing into March, the team generated a variety of possible concepts for the WASP system. These concepts were analyzed and compared, until the team believed that it had a solution to the customer's needs which would meet or exceed all of the stated system requirements. The team's preferred design concept was presented in a Conceptual Design Review (CoDR) at the end of March.

3.2.3 Preliminary Design

The first year of the project closed with the team moving into preliminary design of the selected concept. The team's design focus had shifted away from the development of an operational system and to the design of the prototype systems which would be used for the demonstration program. A Preliminary Design Review (PDR) was held at the end of the term to present the results of this phase of design activity, and the first Master of Engineering class completed their theses.

3.2.4 Test Plan Development

As the team began preliminary design, it also developed a test plan for the prototype systems which would be constructed. The test planning referred back to the risk assessment which had been conducted earlier in the term to determine which elements of the design were the riskiest, and, therefore, should be tested. The output of this planning process was an Integrated Master Test Plan, which showed how testing of various of subsystems eventually lead to larger scale systems tests.

3.2.5 New Student Orientation

An important transition point for the project, the first Master of Engineering class graduated in June. A new class of students joined the team, and time had to be spent familiarizing them with the work already completed on the project and the work for which they became responsible.

3.2.6 Prototype Subsystem Construction

The first phase of testing will be conducted on subsystems of the vehicle. The summer will begin, therefore, with the construction of these subsystems. Detailed software development is included in this "construction" phase, as these programs will be an essential part of the test program.

3.2.7 Prototype Testing and Simulation

Beginning as early as possible, subsystems will start their test programs. Hardware will be exposed to operational environments, and software systems will begin detailed computer simulations. The summer will end with the publication of test results from this phase of testing. These results will determine whether or not the team will progress onto the construction of larger systems prototypes.

3.2.8 Demonstration Vehicle Detailed Design

Incorporating the lessons learned from subsystem tests, detailed design of the demonstration vehicle is planned to run from September to October. A Critical Design Review (CDR) will be held at the end of this period to clear the team to begin construction of the demonstration vehicle.

3.2.9 Subsystem Simulation Integration and Testing

Computer subsystems which had been operating separately will be integrated and run on combined simulations during the first term of the year. These tests will help to reduce the integration risks associated with the final assembly of the demonstration vehicle. Prior to the end of the term, the team will report on the preliminary results of these tests and simulations.

3.2.10 Demonstration Vehicle Hardware Construction

Presuming that the team's plans were approved at the CDR, construction of the demonstration vehicle is planned to begin in October and continue into February of the next year. A considerable amount of time is devoted to this activity due to the likelihood of unexpected problems appearing during the assembly of the system.

3.2.11 Subsystem/Vehicle Integration

As vehicle assembly begins, subsystems will be incorporated as early as possible. This concurrent approach will decrease the assembly time, and allow problems with subsystem integration to be discovered and solved as early as possible.

3.2.12 Demonstration Vehicle Testing/Simulation

The project's final major activity will be the actual testing of the demonstration vehicle. Tests will be designed to validate fundamental aspects of the systems design and operation. In addition, any systems which could not be integrated with the vehicle's hardware will be demonstrated through computer simulation. The ultimate goal of these tests will be to verify the overall approach for the design and to confirm that an operational system will be able to meet operational requirements.

3.2.13 Final Document Preparation

The project will end with the publication of a second set of Master of Engineering theses and several Master of Science theses. In addition to these documents, a final, integrated report will be delivered to Draper Laboratory. This report will cover the entire project, from beginning to end, and serve as an integrated history of both years of effort.

4. Needs Assessment, Requirements Analysis, and Concept Development for the Wide Area Surveillance Projectile

4.1 The Needs Assessment and Requirements Analysis Process

As previously discussed, the concept chosen by Draper Labs for further development was the cannon-launched reconnaissance vehicle. Based on the initial concepts presented by the design team, members of the Draper Laboratory staff and MIT faculty developed an initial list of requirements for an operational vehicle. This document is included in Appendix B. The team logo for the project is shown in Figure 4.1.

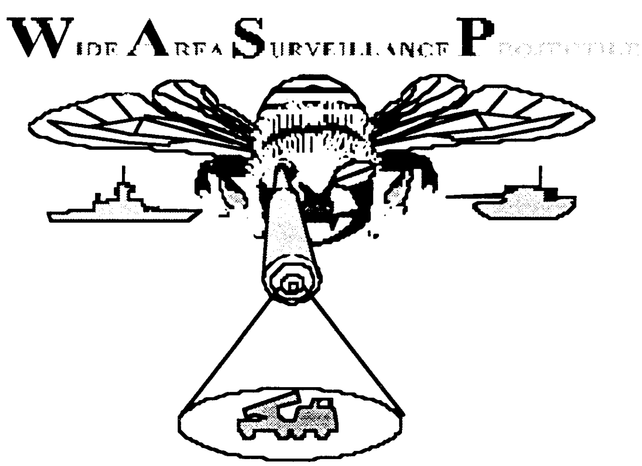

Figure 4.1 WASP Project Logo

After receiving the requirements document, the team entered into a period of needs and requirements analysis, definition, and development. A highly structured method of analysis, information gathering, and further analysis was used to develop a final requirements set for the design project. The sequence followed for this process is shown in an interaction diagram in Figure 4.2.

	Review Requirements Document	Derive Statement of Need	Identify "Driver" Requirements	Mission and Scenario Analysis	Define Goals, Constraints, Requirements	Consult with Operational Community	Develop QFD Requirements Matrix	Conduct Functional Analysis	Develop Top-Level System Architecture	Derive Work Breakdown Structure	Derive Modified System Level Requirements
Review Requirements Document		x	x	x	x	x	x	x	x		
Derive Statement of Need			x	x	x	x	x	x	x		
Identify "Driver" Requirements							x	x	x		
Mission and Scenario Analysis						x	x		x		
Define Goals, Constraints, Requirements							x		x		
Consult with Operational Community	x						x		x		x
Develop QFD Requirements Matrix											x
Conduct Functional Analysis											
Develop Top-Level System Architecture								x		x	x
Derive Work Breakdown Structure											
Derive Modified System Level Requirements						x					

Figure 4.2 Interaction Diagram for the Requirements Analysis Process

As indicated in the diagram, once the team received the requirements document, the first step was to derive a statement of need. All subsequent steps were then carried out nearly in parallel, with feedback provided by consultations with members of the operational community[3]. The final output of this process was a set of modified system level requirements, which reflected some initial design analysis by the team and incorporated feedback from the operational community. This set of derived requirements would then feed into the next step in the design process, preliminary design.

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[3] Details of conversations between the author and members of the operational community can be found in Appendix C. Their input is incorporated throughout this section.

4.2 The Basic Concept

4.2.1 Defining Need: Viewing WASP Relative to Other Reconnaissance Assets

The first question asked by the design team when considering the WASP concept was, "Where does WASP fit relative to other reconnaissance systems currently in use?" Viewing WASP as an isolated capability was unrealistic -- there are many other reconnaissance systems available, and it is reasonable for a customer to ask how WASP would interact with those systems. Ideally, WASP should actually complement the capabilities of these other assets.

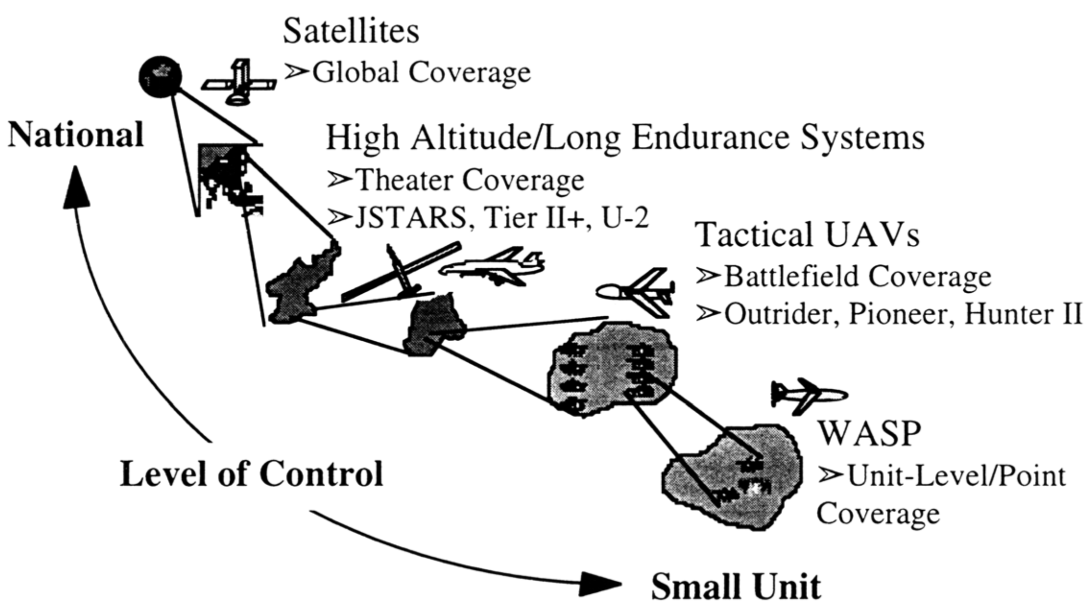


Figure 4.3 Relationships between Reconnaissance Assets

This relationship is depicted in Figure 4.3. At the highest level are the reconnaissance satellites. These systems operate on a global scale, able to view almost any point on the planet. As such valuable assets, they are controlled at high levels within the command structure. A level below these spacecraft are manned and unmanned long range, long endurance systems. Examples of such systems include Joint-STARS, AWACS, the U-2, and the Tier II+ GlobalHawk UAV. These systems can reconnoiter very large areas and can stay on station for very long periods of time. Often controlled at the theater level, these systems are more flexible than satellites, but the data they gather is not immediately available to most warfighters. The next level of assets are the tactical UAVs, such as Pioneer, Hunter, and Outrider. These systems are controlled by smaller units, but these units then disseminate their information to other warfighters. WASP, however, is intended to provide information directly to the warfighter. While it will be able to survey an area smaller than that of the tactical UAVs, but it will be controlled directly by the unit that needs more local information, i.e., the warfighter. In this role, WASP fills a gap at the bottom of the reconnaissance system spectrum, providing small units with the specific intelligence data they need at the moment they need it.

4.2.2 Statement of Need

Based upon the above analysis, the team derived the following statement of need for the system:

> The system's goal is to provide military commanders with a rapid tactical reconnaissance to visually identify high-value, time-critical targets on the battlefield.

This statement defines the basic need to be addressed by the WASP system. It does not, however, specify any restrictions on how that need is to be met. To identify those limits, the team had to analyze the system's requirements in greater detail.

4.2.3 Identifying Constraints and "Driver" Requirements

Keeping the statement of need and its implied design guidelines in mind, the next step in the analysis process was to identify the constraints and primary requirements for the vehicle, i.e., the requirements that would dictate the overall performance, operation, and cost of the vehicle. These factors would serve as a backbone to all of the following analysis and trade studies completed for the design. Drawing from the original requirements document, these drivers were identified as:

- Compatible with Army 155 mm and Navy 5 in. guns -- the primary constraint for the system;
- 70-200 mile range;
- 1-8 hour mission time; 2 hour operational time[4];
- Imaging camera sensor;
- Near-real-time information timing;
- Some degree of autonomous operation (to be determined);

[4] Note: "Operational time" referred to how long the vehicle's sensors systems had to be operated, while "mission time" referred to the total amount of time the vehicle was aloft (even though its sensors may have been off).

- Cost between $20,000-$30,000 per vehicle;
- Self destruct mechanism to limit the size of any debris to no larger than an 8 oz. can of cat food.

In addition to these basic requirements, it was also noted that the vehicle was not intended to be recovered at the end of the mission (hence the inclusion of the self-destruct requirement).

4.2.4 Mission Scenarios

Included in the original requirements document was a basic depiction of the mission envisioned for the vehicle (see Appendix B). In order to assist in the design process, however, the team expanded on this basic scenario based upon system performance requirements. As additional customer contacts were established, these scenarios were revised and updated.

When generating these missions, several factors were considered:

- range: how far the vehicle would have to operate from its point of launch;
- loiter time: how long the vehicle would have to remain over the target area;
- operational time: how long the vehicle would have to be able to collect data and transmit it to the user;
- response time: how much time would be available to prepare the vehicle for launch once it was called upon;
- surveillance area: how large an area the vehicle would have to be capable of surveying;
- customer cost limits: how much the customer would be willing to pay for the capabilities offered by the vehicle.

Table 4.1 provides a comparison of the different missions identified for the vehicle. Following are brief descriptions of these missions.

Table 4.1 Mission Comparisons

Mission	Range	Loiter	Oper. Time	Resp. Time	Surv. Area	Customer Cost Limits
Company Recon	~75 km.	<30 min	<30 min	minutes	1-2 sq. km.	≤$10,000
Damage Assessment	75+ km.	<30 min	<30 min	minutes-hours	1-10 sq. km	$20-$30,000
Signals Intel.	75+ km.	>4 hrs	>4 hrs	hours	1-10 sq. km	$20-$30,000
Comm. Relay	75+ km.	>4 hrs	>4 hrs	hours	1-10 sq. km	$20-$30,000
Route Recon	100+ km.	N/A	= dist ÷ speed	hours	= flt. dist.	$20,000
Scud Hunting	150-200 km.	<30 min	<30 min	hours	1-2 sq. km	$20,000
Hunter/ Killer	100+ km.	>4 hrs	>4 hrs	hours	1-10 sq. km	$20-$30,000
Area Surv.	75+ km.	>4 hrs.	2+ hrs.	hours	≤140+ sq. km.	$20-$30,000
Long Endurance	100+ km.	>4 hrs.	>4 hrs	hours	≤140+ sq. km.	$30,000

Long Duration Missions

These missions were grouped together because they would last more than four hours and would require an imaging or radar-type surveillance sensor payload (see Figure 4.4).

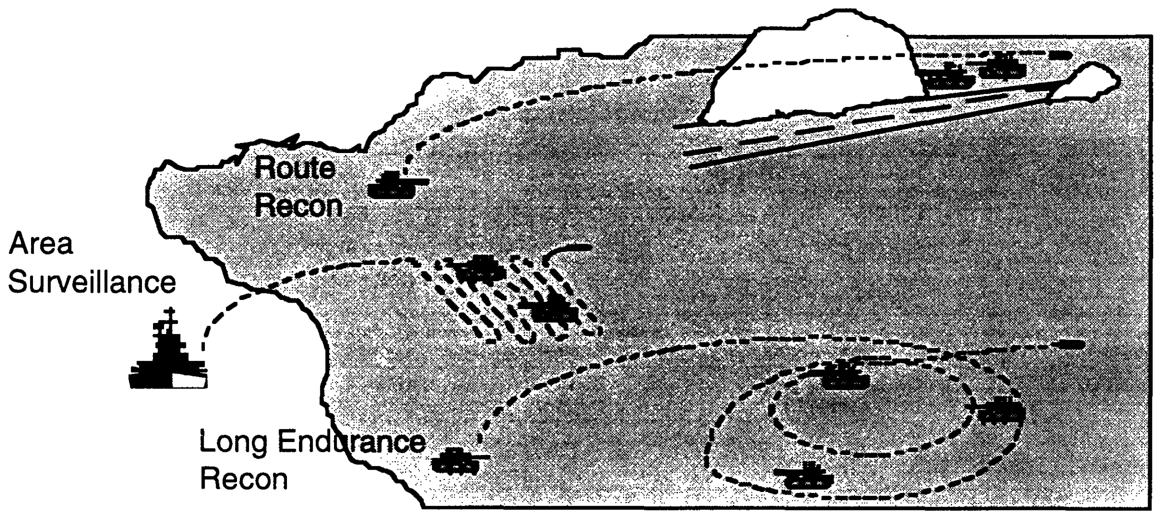


Figure 4.4 Long Duration Missions

Area Surveillance: After being launched, this mission would required the vehicle to survey as large an area as possible. The driving need for this mission was not time aloft *per se*, but rather the amount of land viewed by the vehicle's sensor.

Long Endurance Reconnaissance: This mission was distinguished from the first by the fact that in addition to surveying a large area, the mission required the vehicle to stay aloft for a longer period of time.

Route Reconnaissance: The least demanding of the long duration missions, route reconnaissance would require the vehicle to fly along a preprogrammed path (that would likely be the marching path for an Army unit) and send back images of what was ahead of the unit. The key parameter of this mission was range from the launch point rather than loiter time.

Information Systems Missions

Rather than limiting the payload of the vehicle to imaging or radar sensor systems, the team proposed the possibility of including two types of information system payloads (Figure 4.5).

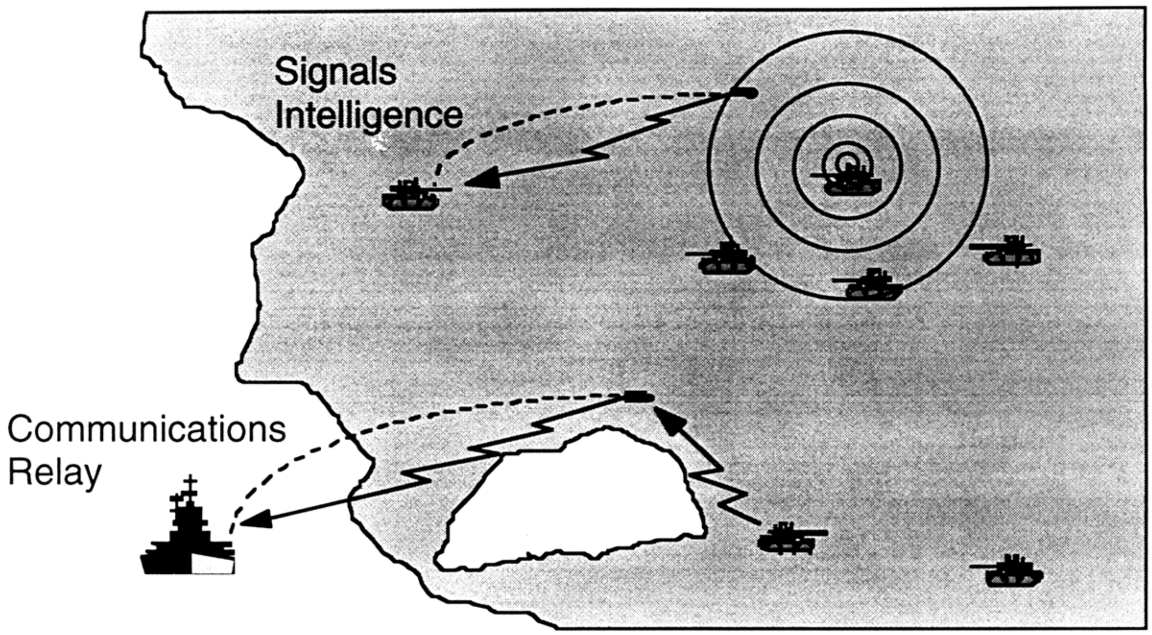


Figure 4.5 Information Systems Missions

Signals Intelligence: This mission would require the vehicle to carry listening devices, to allow a unit to detect and listen to an enemy force's electronic emissions. These emissions might include communications, radar signals, or other similar electromagnetic signals.

Communications Relay: If equipped with communications gear in place of other sensors, the vehicle would serve as a communications relay. In such a role, the vehicle could allow for beyond line-of-sight communications between friendly forces without the need for satellite communications equipment.

Short Duration Missions

Like the long duration missions, a group of missions was identified that would require only a short operational time for the vehicle. These missions are illustrated in Figure 4.5.

Company-Level Reconnaissance: This scenario required the vehicle to be used by smaller-sized military units, at the company level or below. In such a role the vehicle would be used for a "last look" to provide a company or battalion commander with up-to-the-moment information about the region of territory he was about to enter. Such a mission would require a very short operational

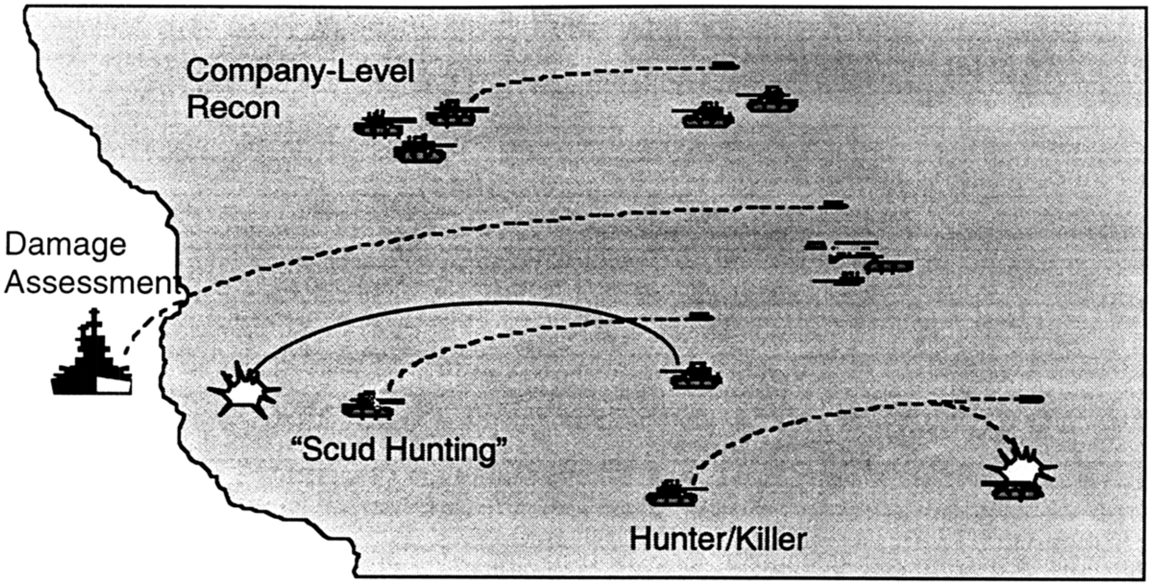


Figure 4.6 Short Duration Missions

time (less than 30 minutes) and would not need to go further than 75 kilometers from the launch point.

Damage Assessment: In this role, the vehicle would be fired shortly after a gun assault on a target. The vehicle would fly out to the target and relay information on the amount of damage sustained by the target. The vehicle's range for such a mission would have to be comparable to that of the weapons used to initially strike the target, but the operational time could be short -- just long enough to take data about a specific, known target.

"Scud Hunting": This mission envisioned a rapid response option to locate mobile tactical ballistic missile launchers, such as those used by Iraq during the 1991 Gulf War. When a missile launch was detected, the vehicle would be fired off in the general area where the missile launch occurred. The vehicle would then begin to search for the mobile launcher as the launcher tried to return to a hiding spot. Though this mission scenario was considered by the team, it was suspected that such an operation might prove too demanding for the vehicle.

Hunter/Killer: Like the Scud-hunting mission, this scenario presumed that the vehicle would be fired toward an area suspected of containing enemy targets. Once over this area, the vehicle would enter a search pattern and look (hunt) for targets. If a target was found and positively identified, it would attack the target with an on-board warhead. The team believed, however, that this mission would also prove difficult to accomplish -- the constrained volume of the shell would limit the space that could be devoted to both electronics and a warhead.

4.3 Reviewing the Requirements

4.3.1 Defining Types and Flexibility

In conjunction with the mission development work described above, the team also reviewed the requirements document to establish the type and flexibility of each specific requirement.

A requirement could be one or a combination of several types: functional, performance, reliability, maintainability, and/or extensibility[5]. Functional requirements described executable actions to be carried out by the system. An example of a functional requirement for WASP was the degree of autonomy. Though not given a specific requirement, the statement that the vehicle incorporate some level of autonomy specified a desired functional capability for the system, i.e., the ability to execute some actions without human intervention. A performance requirement specified how well an executable action must be performed. The range specification for WASP was such a requirement type. Reliability requirements referred to how well an executable action was performed over time. These requirements are typically stated in terms of Mean Time Before Failure (MTBF) -- how long a system can be expected to operate properly until a failure occurs. Maintainability requirements specified how well a system can be fixed if a failure occurs. The maintainability for WASP was stated in terms of a shelf life and the inclusion of provisions to allow for the replacement of expendable supplies on the vehicle while in storage. Finally, extensibility requirements described the ability of the system to adapt to changes or new requirements. WASP's extensibility requirement was described in terms of several items, including the consideration of a variety of sensor payloads, all-weather operations, and the exploration of civilian applications.

In addition to being described in terms of types, the requirements were also described in terms of degree of flexibility: constraint, requirement, operational requirement, or goal. A constraint was a statement that usually included the word "must" and could not be traded -- such a

[5] G. Chambers, *Requirements: Their Origin, Format, and Control.* NCOSE, 1992, and Charlie Boppe, Lecture Notes for 16.870, *Aerospace Product Design*, 1997.

requirement must be met by the design. One of WASP's most important constraints was that it be compatible with existing gun systems. Slightly more flexible than a constraint, a requirement offered some degree of "tradability." WASP's range and loiter times were both examples of requirements. Even more tradable, an operational requirement described desired features, but features that may be traded to improve performance in more important areas. The degree of autonomy stipulated for WASP was considered an operational requirement: were it to interfere with achieving other system goals, the degree of autonomy could have been reduced. Lastly, a goal was a requirement that the customer desired but did not absolutely demand, i.e., would be willing to trade it to improve the system's performance in any other area. A goal originally identified for WASP was the price range, initially estimated at $20,000 to $30,000 per vehicle.

In addition to using these definitions to improve the team's understanding of the requirements, several other checks were applied to the requirements document: whether or not the requirement could be verified (during the course of this project), how ambiguous the requirement was, how susceptible the requirement was to change, and whether or not the requirement conflicted with any of the others. The purpose of defining these additional metrics was to prepare the team for changes that the customer might specify in the future and to help the team gain a better understanding of where trades could be made. In addition, by identifying conflicting requirements early in the process, it was hoped that the detrimental effects of these conflicts could be mitigated. It was also important to list a requirement as easy or difficult to verify to aid the team when attempting to design a prototype vehicle. If a requirement was easily verifiable, there might be no point in designing a test for it. If the requirement could only be verified by testing, that too would be very important to know prior to designing a prototype. Establishing these standards for the requirements would, therefore, prove useful later during the design process, helping the team to judge design trades and to design and develop a test plan.

The entire requirements document was reviewed using these definitions and standards. The results are presented below in Table 4.2.

Table 4.2 Requirements Document Assessment

Requirement	Type	Flexibility	Verifiable	Ambiguity	Susceptible to Change	Conflict
Range: 70-200 miles	Perform	Rqmt.	Yes	Wide variation in specified values	Yes	Loiter, oper. time; cost
Loiter: 1-8 hours	Perform	Rqmt.	Yes	Wide variation in specified values	Yes	Range, loiter; cost
Operational Time: 2 hours	Perform	Rqmt.	Yes	No	Yes	Range, loiter; cost
Surv. Area: self-sustained Marine Brigade	Perform	Rqmt.	Yes, but possibly difficult due to ambiguity	Yes -- def'n of "area of action"	Yes	Range, loiter, operational time

Requirement	Type	Flexi-bility	Verifiable	Ambiguity	Suscept-ible to Change	Conflict
Projectile Size: Existing 155mm or 5 in. diameter, length consistent w/similar rounds	Funct./ Extens.	Diameter: Constr. Length: Rqmt.	Yes	155mm and 5in are different sized rounds....	Length may be; diameter is not	Severe volume limits & possible shape limitations for other components
Location Accuracy: Several Meters	Perform	Rqmt.	Yes	"Several" is very inexact	Yes	Unknown
Sensor Type: Imaging Camera	Funct	Goal	N/A	No	Possible other variants (see below)	Size and power constraints
Self Destruct: 8-oz. debris	Perform	Oper. Rqmt.	Yes	No	Yes	Unknown
Acquisition Cost: $20-30,000	Perform	Goal	Probably only when ready for production	No -- includes cost of projectile, flyer, and sensor, but not ground station	Yes	Advanced technology may raise cost; long oper. & loiter times
Information Timing: Near Real-time	Perform	Rqmt.	Yes	Yes -- rqmt is very inexact ("near")	Yes	Unknown
Level of Autonomy: TBD	Funct	Oper. Rqmt.	N/A	Yes	Yes	Unknown
Existing Constraints: Use as an organic asset in local theater ops.	Funct	Constr.	Unknown	Yes	No	Cost
Existing Constraints: 250-Hz spin rate to 0 spin @ launch	Funct/ Perform	Goal	Yes	Yes -- is this a rqmt or design necessity?	Yes	Increase complexity (cost)
Environment: 10,000+ g's	Perform	Constr.	Yes	Yes -- "increase if integrated projectile results in lighter weight"...?	Yes (?)	Unknown
Shelf Life: Approx. 20 yrs. w/provision for repl. batteries, etc.	Maint	Rqmt.	Not without long term testing	No	Yes	Unknown
Covertness Level: Low RADAR, visual, acoustic signatures	Perform	Constr.	Yes -- RCS, dB, etc.	No	No	Cost, aero (range, loiter), sensor options (limit transmis-sions)
Extensibility: comm. network; all-weather ops.; RADAR, IR, motion sensors; civil missions	Extens	Goal	N/A	No	Yes	Possible: cost, packaging

Requirement	Type	Flexi-bility	Verifiable	Ambiguity	Suscept-ible to Change	Conflict
Prep. and Launch Time: 2-3 min.	Perform	Rqmt.	Yes	No (Assuming time from order is received until vehicle is launched)	Yes	Unknown
Safety: As safe or safer than existing munitions	Perform	Constr.	Yes	No	Yes	Unknown

4.3.2 Quality Function Deployment I: The Requirements Matrix

The next step in the requirements analysis process was the quality function deployment exercise. The basic purpose of a QFD matrix, often referred to as the "house of quality" due to its appearance, was to help the team prioritize the system requirements from the customer's point of view. The first of these matrices generated was the Requirements Matrix. Using this matrix, the team expanded the system requirements given in the original requirements document to generate technical system requirements[6].

The first step in generating the QFD matrix was to prioritize the original requirements. The priority ranking, generated by the team based upon discussions with members of the operational community, is shown in Table 4.3. On this table, the higher a score, the more important the requirement was to the customer, 10 being the highest possible score, 1 the lowest. As indicated in the table, the customer's highest priorities were long loiter, long operational time, low cost, and ease of operations. Note that "ease of operations" was not an explicit requirement from the requirements document, but was a requirement generated by the team based upon the functional analysis (discussed below) and consultations with the operational community.

[6] For detailed description of QFD methods see John R. Hauser and Don Clausing, "The House of Quality," Harvard Business Review, Vol. 66, Iss. 1, 1979, p.63.

Table 4.3 Requirements Prioritization

Customer Needs	*Importance (1-10)*
Long Loiter	10
Long Operational Time	10
Low Cost	10
Ease of Operations	10
Very Safe	10
Accurate Image Position Det.	9
Near Real-Time Info. Processing	9
Ease of Maintainability	9
Max. Field of View	8
Max. Image Resolution	8
High Degree of Autonomy	8
High Reliability	8
Long Range	5
Strong Stealth Characteristics	5
High Extensibility	5
Min. Self-Destruct Debris	4
Long Shelf Life	4
Short Launch Time	3

Referring back to the earlier analysis of the requirements, it was quickly apparent that the customer's priorities conflicted with one another: the requirements for long loiter and long operational time were expected to conflict with a low system cost. One aspect of these conflicting requirements that helped the design process, however, was that although low cost and long operational and loiter times were the customer's highest priority, these requirements were also fairly "tradable"(see Table 4.2). Long operational and loiter times were both assessed as requirements, implying that they were somewhat tradable, while cost was assessed as a goal, meaning that it could be traded to improve the system's performance in other areas. This freedom to make trades between these conflicting requirements would prove essential downstream in the design process, allowing the team to trade one aspect of the system's performance to meet other demands.

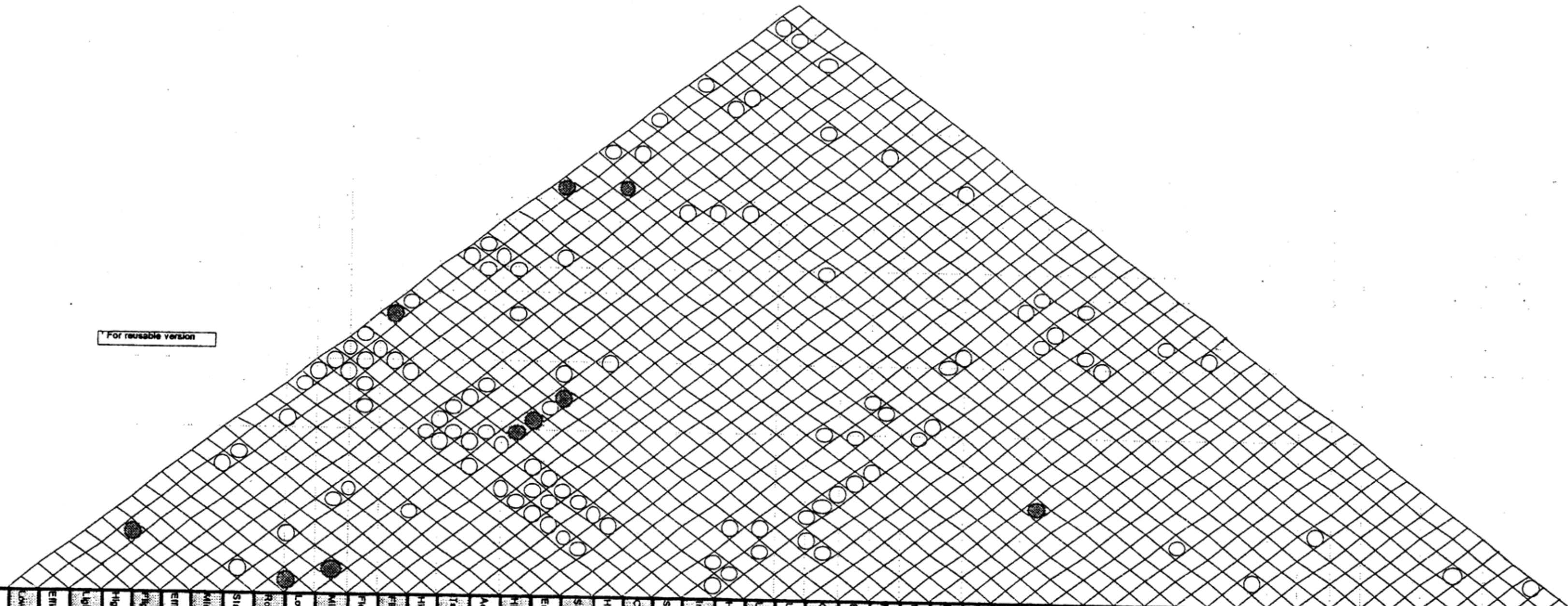
Other high ranking requirements included accurate image position determination, near-real-time information processing, and ease of maintainability. The maintainability and position accuracy requirements were derived by the team based on analysis of the original requirements document in conjunction with customer feedback. The maintenance requirement was generated to help the design meet the goals for cost, existing organizational constraints, shelf life, reliability, extensibility, and preparation time. All of these requirements included some need to access components on the vehicle, and the team felt that these diverse needs warranted additional attention in the form of a maintainability requirement.

The requirement for accurate image position determination was derived by the team based on the functional analysis of the system (see below). After reviewing the functional flow for the vehicle and receiving feedback from customers and engineers at Draper Labs, the team came to realize that what was important to the customer about our system was not the physical components of the system, but the information which it returned. Thus, what was important to the customer was not the capability to determine where the vehicle was flying (though that capability might be important for navigation), but the capability to determine an object's location in an image taken by the vehicle's sensors.

Interestingly, though the vehicle's primary mission was information gathering, the team learned that users were willing to sacrifice image quality for longer loiter time or low cost. Users expressed the opinion that unless the image quality was very high, they often would prefer slightly worse image quality in exchange for better performance in other mission characteristics. This opinion was the reason that image-related requirements were ranked lower than one might expect.

With the requirements finally listed, the next step in the quality function deployment process was to brainstorm several technical requirements for each customer requirement. These technical requirements would eventually serve as a foundation from which to develop detailed component requirements for the operational system. As such a foundation, the technical requirements formed a bridge between the desires and words of the customer and the technical specifications and methods of the engineers on the team.

As each technical requirement was developed, its influence on all of the customer requirements was noted in the matrix by either an empty space (no influence), a one (weak influence), a three (moderate influence), or a nine (strong influence). The score for each technical requirement was then tallied, and a total score for the technical requirement was generated. This total score was then divided by the sum of all of the scores for the technical requirements to generate a relative score. The so-called "roof" of the matrix was then filled out, dark circles indicating conflicts between important (i.e., high scoring) requirements, empty circles indicating conflicts between less important requirements. The entire matrix is shown in Figure 4.7, while Table 4.4 lists the most important technical requirements.



Customer Needs	Importance	Low inert mass fraction	Efficient aerodynamic design	Lightweight materials	High energy density	Flight path control	Efficient on-station propulsion	Minimize component size	Staging	Robust power system	Low subsys. power reqt
Long range	5	9	9	9	3	9	9	3	3	1	1
Long loiter	10	9	9	9	9		9	9	9	9	3
Long operational time	10	3	3	9	9	3	3		3	9	9
Maximum field of view	8					1	3				
Maximum image resolution	8					1	3				
Acc. image pos. determination	9										
Minimum self-destruct debris	4							3			
Low cost	10	3							3		
Near real-time info. processing	9									1	
High degree of autonomy	8				3	3	1			1	
Long shelf life	4									1	
Strong stealth chars	5			3				1			3
Ease of operations	10			1		3					
Ease of maintainability	9										3
High reliability	8									3	
High extensibility	5	3	3	3	1	3	3		3	3	
Short launch time	3										
Very safe	10										
Technical Importance	2637	218	180	265	224	169	236	122	184	245	227
		8	6	10	8	6	8	4	6	9	8
Objective Target Values		0.2	23:1 glide slope	carbon-fiber	400 Whr/kg						

Customer Needs	Importance	Minimal delivery basket	Flexible sensor system (zoom)	Flight system disturbance rejection	High sensor pointing acc.	Target recognition capability	Accurate Navigation	High platform stability	Easily destroyable parts	Self-destruct mech	High design commonality
Long range	5										
Long loiter	10	3					1				
Long operational time	10	9	3	3							
Maximum field of view	8		9					1			
Maximum image resolution	8		9	9	9	9		3			
Acc. image pos. determination	9		1	9	9	3	9	9			
Minimum self-destruct debris	4								9	9	
Low cost	10										9
Near real-time info. processing	9			1							
High degree of autonomy	8			3		3	9				
Long shelf life	4										
Strong stealth chars	5										
Ease of operations	10		3	1			1				1
Ease of maintainability	9										3
High reliability	8			3							3
High extensibility	5		3	3	3	3	3	3		3	9
Short launch time	3										
Very safe	10							1	3	1	
Technical Importance	2637	120	228	265	188	138	198	138	66	66	196
		4	8	10	6	5	7	5	2	2	7
Objective Target Values									cat food can	cat food can	

Customer Needs	Importance	COTS/standard components	Simple mfg & assem	Inexpensive components	High data throughput	Large bandwidth comm.	Long range comm.	On board intelligence	Environmentally robust subsys.	Minimize transmissions	Low visual signature
Long range	5										
Long loiter	10										
Long operational time	10										
Maximum field of view	8				1	3					
Maximum image resolution	8				9	9					
Acc. image pos. determination	9										
Minimum self-destruct debris	4										
Low cost	10	9	9	9							
Near real-time info. processing	9				9	9	3	3			
High degree of autonomy	8				3	3	3	9		3	
Long shelf life	4								9		
Strong stealth chars	5									9	9
Ease of operations	10	3			3	3	3	3	1		
Ease of maintainability	9	3	3					3			
High reliability	8								3		
High extensibility	5	9				3	3				
Short launch time	3										
Very safe	10							3	3		
Technical Importance	2637	195	120	98	220	246	161	202	120	79	60
		7	4	3	8	9	3	7	4	2	2
Objective Target Values				total < $30,000			70-200 miles				

Customer Needs	Importance	Low RADAR signature	Low acoustic signature	Low IR signature	Simple user interface	Similar handling chars. to peers	Maximize Automated Fxns	Minimize operator training	Robust shell	Effective diagnostics	Component accessibility
Long range	5										
Long loiter	10										
Long operational time	10										
Maximum field of view	8										
Maximum image resolution	8										
Acc. image pos. determination	9										
Minimum self-destruct debris	4										
Low cost	10				3		3	3		3	3
Near real-time info. processing	9										
High degree of autonomy	8				1		9				
Long shelf life	4					1			3		1
Strong stealth chars	5	9	9	9							
Ease of operations	10				9	9	9	9	9	3	
Ease of maintainability	9				3	3			9	9	9
High reliability	8								3		
High extensibility	5				3						1
Short launch time	3				3	3	3	1			
Very safe	10					3			3		1
Technical Importance	2637	60	60	60	179	160	203	131	237	149	130
		2	2	2	6	6	7	4	8	5	4
Objective Target Values						same shell size/shape					

Customer Needs	Importance	Minimal Mechanical Systems	Proper payload loading (g's)	Reliable components	High MTBF*	High g components	Weather resistance	Sensor modularity	Adaptable on-board intell.	Minimal system prep	Fail-Safe Design Concept	Mistake-Proof Mntnce. Concpt
Long range	5						1					
Long loiter	10						3					
Long operational time	10			1			3		1			
Maximum field of view	8											
Maximum image resolution	8											
Acc. image pos. determination	9											
Minimum self-destruct debris	4											
Low cost	10	3										
Near real-time info. processing	9								3			
High degree of autonomy	8								9			
Long shelf life	4	3		1	3		3					
Strong stealth chars	5											
Ease of operations	10			3				3	3	3		
Ease of maintainability	9	9						3				
High reliability	8	9	9	9	9	9	9					
High extensibility	5		3				3	9	9			
Short launch time	3							3		9		
Very safe	10		1	3	3	3					9	9
Technical Importance	2637	195	97	154	114	102	164	111	164	75	90	90
		7	3	5	4	3	6	4	6	2	3	3
Objective Target Values			>10,000 g's			>10,000 g's	water proof					

Figure 4.7 The QFD Requirements Matrix

Table 4.4 The Most Important Technical Requirements

Technical Requirement	Technical Importance	Relative Importance
Flight System Disturbance Rejection	265	10
Lightweight Materials	265	10
Large Bandwidth Communication	246	9
Robust Power System	245	9
Robust Shell	237	9
Efficient On-Station Propulsion	236	9
Flight Sensor System	228	9
Low Subsystem Power Requirement	227	9
High Energy Density	224	8
High Data Throughput	220	8
Low Inert Mass Fraction	218	8
On-board Intelligence	202	8
Maximize Automated Functions	201	8
Accurate Navigation	198	8
High Design Commonality	196	7
COTS/Standard Components	195	7
Minimal Mechanical Systems	195	7

As indicated in Table 4.4, the most important technical requirements turned out to be flight system disturbance rejection and lightweight materials. Flight system disturbance rejection was a term derived by the team to express a need to ensure that the images taken by WASP's sensors would be clear and easy to view, i.e., free of vibrations or jitters caused by mechanical systems in the vehicle, wind gusts, etc. The phrase's vagueness was intentional -- the team did not want to constrain the design early in the process by listing a requirement for a specific system to meet this need (such as a gyroscopically stabilized gimbal system for the sensor). While the high score of this requirement was surprising to many on the team, its importance does make a great deal of sense, especially when viewed in terms of the customer's primary need: what is ultimately important to the customer is not the system itself but the quality of the information it delivers. If any images sent back by WASP turned out to be difficult to view, whether the cause be mechanical vibration from the motor or a sudden gust of wind, the entire system could prove useless.

The other highest scoring technical requirement for WASP was lightweight materials. This result was fairly predictable based on trends with more traditional air vehicles. Light vehicle weight often resulted in lower cost and better range and loiter performance for aircraft, all three of which were high ranking customer requirements for WASP.

The next tier of technical requirements included several that would become very dominant throughout the coming conceptual design phase of the project. The need for large bandwidth communications was derived from the necessity to transmit imagery taken by the vehicle's sensors. The only other method to recover the data would be to retrieve the vehicle after its mission, but the vehicle was intended *not* to be recovered. In addition, since WASP was to billed as a rapid response reconnaissance asset, it would be important that the data it collected be returned quickly. Additionally, although the team was already beginning to formulate its interpretation of the autonomy requirement, it was widely recognized that some communication with the vehicle beyond the transmission of reconnaissance data would be desirable and possibly necessary. This line of thinking came again from the functional flow analysis (discussed in the next section), in which the team believed that the customer might appreciate the ability to retask the vehicle in flight, if, for instance, an unexpected target of interest appeared outside of the original flight path. Such a retasking order would require two-way communication between WASP and the unit operating the vehicle. Finally, given the experience of present day UAV systems, the team believed that it would be wise to allow for humans to intervene in the vehicle's operation. Taken together with the original requirements for the vehicle, large bandwidth communications became a high priority.

Several of the other second level technical requirements related specifically to the vehicle's power systems: robust power system, efficient on-station propulsion, and low subsystem power requirements. All of these requirements came from the need for long range and long loiter, and also had some effect on other requirements (see the QFD matrix in Figure 4.7).

Among the third tier technical requirements, those relating to the vehicle's automated systems and the energy density of the power system would prove important throughout the design phase. The requirements document left a large degree of latitude for the team to determine how autonomous WASP would be. Based on research being conducted in conjunction with the requirements analysis (and discussions with potential customers in particular), the team concluded that the autonomy should be used in the design to help keep the system easy to use. By making WASP itself highly intelligent the hope was that operators would not have to be highly trained to operate the system. The team suspected that this intelligence would come in the form of "point and click" control, in which the user would simply have to point to a location on a computer display and the vehicle would navigate to that point autonomously.

Providing power for WASP's subsystems was another major challenge of the design. Due to a variety of factors, the vehicle's limited size and the high-g environment in particular, the team was always concerned that it would difficult for the vehicle to carry an energy source which would provide enough power to meet the operational time requirements and also fit within the shell. These concerns led to the development of the high energy density requirement, which basically stated the need to have as much power per unit volume as possible.

The final set of technical requirements listed in Table 4.4 affected the rest of design process to varying degrees. The intent of the first two, high design commonality and the use of commercial off the shelf (COTS) and standard components were intended to help contain the system's costs. Rather than building all unique parts, the team felt that it would be important to adapt as many existing components as possible. In addition, the high design commonality requirement was intended to stress the need that parts and systems from existing artillery shells should be used to ensure that WASP would be compatible with existing gun systems. Together with the potential reduction in cost, the team hoped these technical requirements would meet the cost and compatibility requirements originally specified for the system.

Finally, the technical requirement to minimize the number of mechanical systems was based on the need to survive the extreme conditions of the cannon launch environment -- forces of up to 20,000 to 30,000 times the force of gravity -- and to accomplish the transition from ballistic cruise to aerodynamic-supported loiter as reliably as possible. First, in terms of the launch environment, it was felt that moving parts would be highly susceptible to failure, particularly at joints, when subjected to the launch loads. If such fears were to be averted, joints would have to be structurally reinforced, leading to increased weight. To avoid such detrimental effects, the team felt the best approach would be to simply minimize the number of joints, i.e., mechanical systems. In addition to the these factors, the team also believed that minimizing the mechanical systems would improve the system's reliability during deployment. This belief was based primarily upon a lecture given by Mr. Thomas B. Coughlin from the Johns Hopkins University Applied Physics Laboratory (APL)[7]. During their design work for the NEAR spacecraft, engineers at APL took the approach that as many mechanical systems as possible should be removed, and fixed units used in their place, even if performance was somewhat degraded. The feeling at APL was that any loss in performance would be compensated by increased reliability, lower system complexity, and reduced cost. The MIT/Draper team attempted to follow this design guideline given the similar need for high mechanical reliability.

Development of the QFD matrix was an iterative process, and the details of the matrix changed slightly throughout the project as more information became available, particularly from the operational community. The discussion presented above represents the integration of these changes over time. In addition, since the process is iterative, the matrix described in this section should be revised by the team now that it has completed its preliminary design.

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[7] Lecture given by Mr. Thomas B. Coughlin at the Massachusetts Institute of Technology, November 14, 1996.

With the first iteration of the matrix completed, however, the team began to shift its emphasis away from requirements analysis and toward the first steps of conceptual design.

4.4 Initial Systems Architecting

Systems functions were identified using functional flow analysis, and then architectural elements were conceived to execute these functions. As these elements were identified, however, some of the functions were modified, some removed, and new ones added. The following sections present the final results of this initial process.

4.4.1 Functional Flow Analysis and Diagram

Developed concurrently with the top-level systems architecture, a functional analysis of the requirements was implemented to aid in the understanding of the system requirements. The purpose of this functional analysis was broad-based. In the most general sense, this analysis simply helped the team understand what WASP would do during a mission. At a deeper level, however, the functional analysis also helped to reveal system functions not expressly laid out in the requirements document. The functional analysis also helped the team develop an understanding of how the functional requirements interacted with one another during the course of the system's operation. Finally, the functional analysis would be a critical tool in developing a top-level architecture for the system. Following the old saying, "Form follows function," the team would use the functional analysis to assign functions to elements of the system architecture.

The goal of this development sequence -- requirement to function to architecture -- was to ensure that the team did not lock onto a single design solution. Instead the objective was to work from the top down, understanding the needs and functions of the overall system and then eventually decomposing these top-level requirements and functions so that they could be assigned to a specific piece of hardware or software. As these parts were incorporated into the final vehicle, the functions would again be integrated to provide the overall functionality of the complete system.

The functional analysis conducted by the design team focused on the development of a functional flow diagram (FFD). This diagram was essentially a time-sequenced flow chart, listing the various executable actions of the system and showing how one such action flowed into the next. The basic structure of the FFD, therefore, was a series of boxes, each specifying a function, linked by arrows showing relationships. A function, for this purpose, was specified as an action verb followed by a noun. What became known as the baseline FFD for WASP is shown in Figure 4.8. This FFD showed the flow of executable actions for the reconnaissance mission specified in the original requirements document. Several additional variants of this flow were developed for the other missions developed by the team, and they are included in Appendix D.

Several aspects of the functional flow diagram warrant specific consideration. First note that when the team developed the FFD, it also began to develop the beginnings of a system architecture. The team identified three elements: the flyer, the shell, and the ground station. Functions were assigned to the flyer/shell combination, the shell alone, the flyer alone, or the ground station.

Two functions which the team knew would have a dramatic impact on WASP's design were "Undergo Loading into Gun" and "Undergo Cannon Launch." The vehicle would have to be designed to be robust enough to survive any mistreatment to which it might be subjected while being handled for loading, such as being accidentally slammed into the gun's structure, for instance. This function implied that the vehicle not only have a strong exterior structure, but that any protrusions, such as fins or antennas, should be avoided. Subsequent to being loaded, the vehicle would then have to survive the gun launch environment. The vehicle would be subjected to forces measuring tens of thousands of times the force of gravity, in addition to being subjected to significant side forces as it traveled through the barrel. The rifling in the barrel would also make the vehicle spin at speeds up to 250 Hertz (as specified in the original requirements). It was clear that the magnitude of these forces would become driving factors in the design of the vehicle.

Another function which the team expected would pose a significant challenge was "Deploy for Cruise Configuration." During this phase of the mission, the vehicle would have to switch from spin-stabilized, ballistic flight to a more efficient cruise configuration. At this point in the design process, the team did not know how this transformation would occur. The assumption that was made, however, was that the flyer would separate from the shell, stabilize itself, and then continue with its mission. The shell would be discarded at that point, and, as specified in the requirements document, destroyed. An option was included in the baseline FFD, however, for the shell to deploy a parachute to allow for a soft landing on the ground.

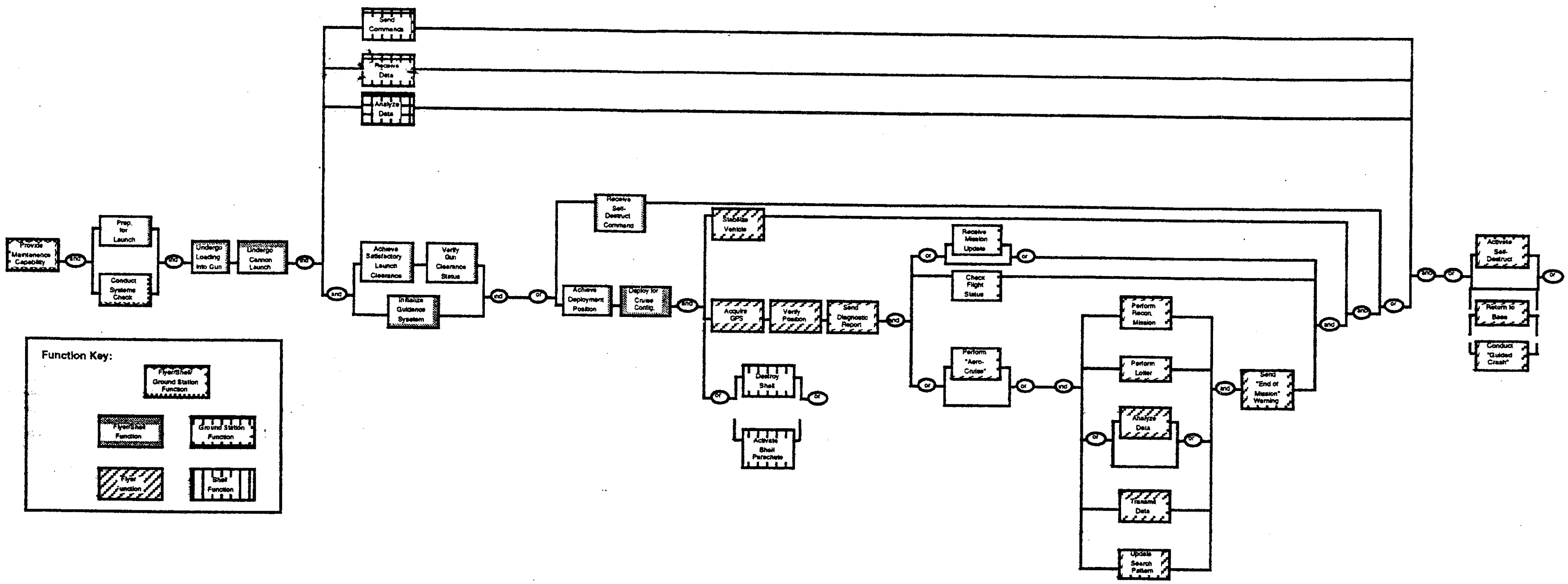

Figure 4.8 Baseline Functional Flow Diagram

The primary segment of the mission was illustrated in the FFD by a large set of parallel activities, including "Perform Reconnaissance Mission," "Perform Loiter," "Analyze Data," "Transmit Data," and "Update Search Pattern." It was assumed that once the flyer was on station, all of these activities would be conducted simultaneously. Note that the functional flow diagram implied that the flyer possessed enough on-board computer power to conduct some image analysis prior to transmitting the data. This initial assumption was later shown to be invalid, and any similar functions were shifted to the ground station only.

Throughout the FFD, functions were identified which would be used to help define the system's degree of autonomy. Such functions included "Verify Position," "Check Flight Status," and "Perform Reconnaissance Mission." These functions all implied that the vehicle would have some capability to sense its environment to facilitate navigation, that it would be able to monitor its own operation, and that it would be able to control some aspects of its mission planning and execution. The team spent a considerable amount of effort deciding exactly what functions to automate and which would remain under human control.

Several options were considered for the end of the flyer's mission. The requirements for WASP stated that the vehicle destroy itself at the mission's conclusion, and this function was listed on the FFD. In addition, the team also noted three other options. A straight line indicated that the vehicle could simply crash into the ground once it had completed its mission. Another option was to have the vehicle return to its base, potentially allowing for it to be used again. The final option considered was have the vehicle conduct a guided crash landing at the end of the mission.

Also noted on the FFD were the three primary functions of the ground station: "Send Commands," "Receive Data," and "Analyze Data." The ability for the ground station to send commands was mirrored by the flyer function, "Receive Mission Update."

The functional flow diagram formed the foundation for the design effort to follow. Functions were first be assigned to architectural elements, and these elements were used to design the WASP systems, subsystems, and specific components.

4.4.2 Identifying Architecture Elements: The Top-Level Systems Architecture

Having reviewed the requirements in great detail and conducted a systems level functional analysis, the next step in the design process was to assign functions to system elements. After several iterations, a top-level systems architecture was identified for the WASP system. This architecture is shown first as an architectural block diagram in Figure 4.9 and then in illustrated form along with external system interfaces in Figure 4.10.

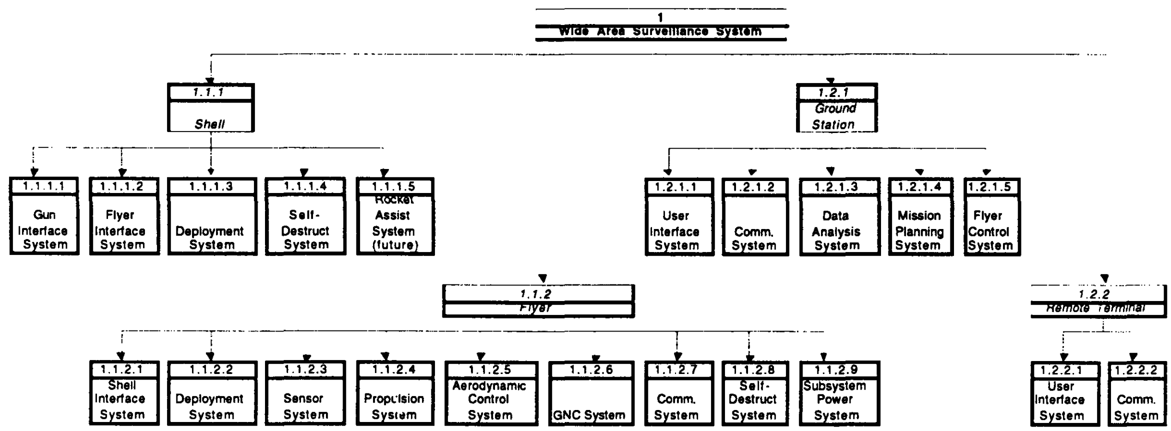

Figure 4.9 WASP Architectural Block Diagram

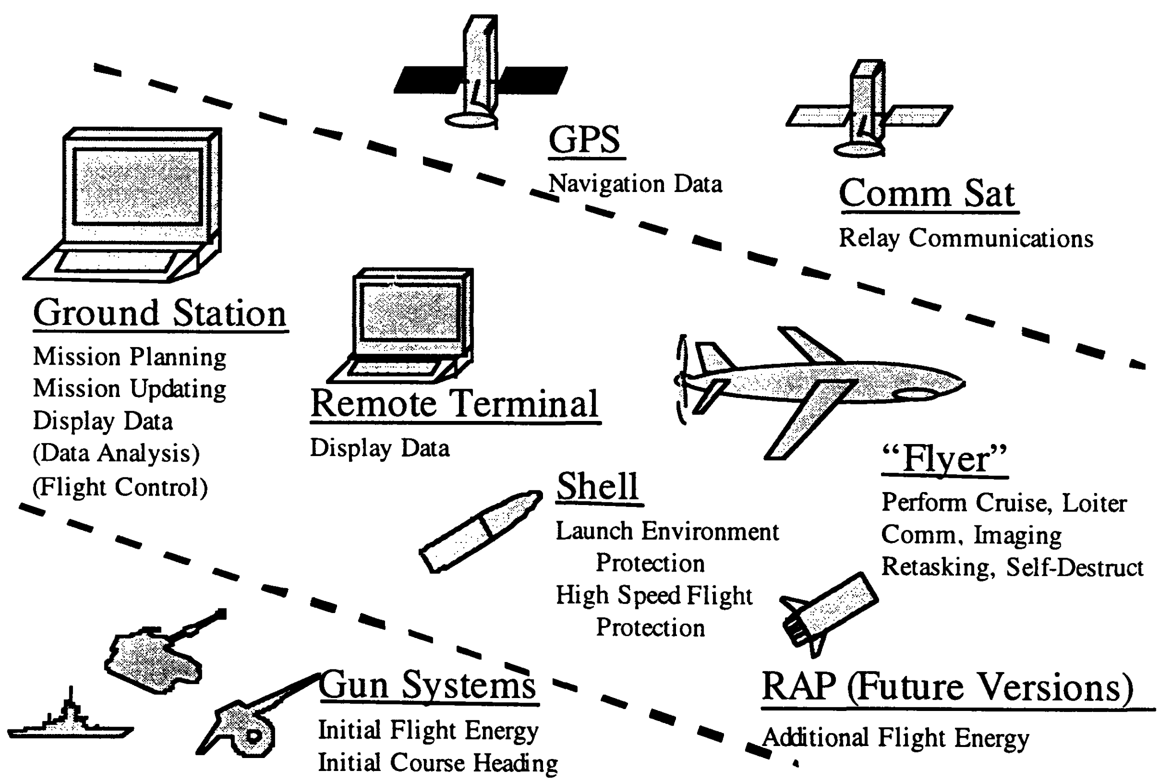

Figure 4.10 WASP Top-level System Architecture

As depicted in Figure 4.10, the elements shown inside the two dashed lines are WASP system components; elements shown above and below the lines represent systems external to WASP, but with which WASP must interface. These top-level elements are described below.

WASP Elements

Ground Station

The ground station was conceived to provide an interface between the human user of WASP and the reconnaissance systems. At the beginning of a mission, the ground station would be used to plan WASP's flight path and reconnaissance mission. Once planned, the ground station would be connected to the vehicle and the mission plan downloaded. After the vehicle had been deployed and was operating, the ground station would receive the images taken by WASP's sensors. This data would then be displayed to the user. Based on the information, the user could then update WASP's flight path, most likely by "pointing and clicking" on points on the display. Additional functions that could have been assigned to the ground station included data analysis and flight control. The data analysis feature might have included some degree of automatic object recognition capability, while the flight control feature would have allowed for more direct intervention in the WASP's flight trajectory by the user (i.e., through the use of a joystick to control the vehicle like a remote control aircraft).

It is important to note that the team initially hoped that an existing ground station could be modified for use with WASP. This hope was driven by the customer requirements for low cost and ease of operation, which had led to the technical requirements for the use of standard components and high design commonality. It was felt that rather than "reinventing the wheel," the team might be able to save time and cost in the project development and then the system's operation if a ground station already in use could be adapted to our needs.

Remote Terminal

The inclusion of a remote terminal in the top-level architecture was driven by two factors. First was the feedback from the user community of the importance of putting information into the hands of the warfighters. Currently, many UAVs are controlled by special units. These units are then responsible for disseminating the information their UAVs gather to other units. Current trends in the armed services, however, are to shorten the path reconnaissance information must travel to get to the user. The design team attempted to recognize this trend from the beginning of the project by including an element that a warfighting unit (as opposed to the unit controlling the UAV) could easily transport. This small interface device would allow for a limited degree of interaction with WASP, most likely only displaying the imagery sent back by the vehicle, but not allowing any vehicle control.

The second factor that led the team to include the remote terminal was the realization that the unit requesting a WASP mission might not be the unit controlling the artillery guns used to launch the vehicle. In current force structures, one artillery unit may support several other infantry or armor units. The team believed that there would be a high likelihood that one or several of these other units might be the unit(s) requesting a WASP mission, but the artillery unit would still be responsible for preparing and launching the vehicle. Under these circumstances, the artillery unit might control the ground station while the other units were equipped with remote terminals. Depending upon the desired degree of control, the remote terminals might be equipped to send commands to WASP directly or indirectly through the ground station. Whatever level of control was eventually implemented was not the initial concern of the design team; the team was instead interested in ensuring that some remote terminal capability was included in the design.

A Note on Navy versus Army Operations

The above discussions of the ground station and remote terminal were clearly focused on the use of WASP by Army units. The architecture, however, is still valid for use by naval units as well. Three scenarios can be imagined in the naval realm. In the first, the ground station is contained in one ship, while the imagery is disseminated to other vessels which contain remote terminals. In the other case, the ground station is again located on one ship, but the remote terminals are controlled by land units being supported by the ship. Finally, the third scenario would have the ground station controlled by a land unit with a naval vessel receiving data via a remote terminal.

Shell

One of the constraints for WASP was that it be launched from the Navy's 5 inch or the Army's 155 millimeter guns. A major architectural element for WASP, therefore, was the system that would enable the interface between the UAV and the gun. This element would have to be capable of supporting the vehicle under the extreme impulse exerted by these guns upon firing -- forces on the order of 20,000 to 30,000 times the force of gravity. In addition to supporting these enormous loads, the interface device would also have to absorb the rifling of the gun barrels. Most modern artillery guns have rifled barrels which spin the projectile to stabilize their flight. This rifling would actually cut grooves along the surface of the projectile, at the points where the projectile rubbed against the barrel. The interface device would have to ensure that these effects would not damage the UAV itself. Finally, this device would also have to mimic the flight of the shell, at least during the initial flight of the vehicle. Since at the beginning of the project the team did not have a clear vision of what form this device would eventually take, this element was simply labeled "shell" and was understood by the team to represent the element of the design enabling the interface to the gun.

Rocket Assisted Propulsion Unit (RAP)

Army artillery units already have some shells which have a rocket motor attached at the back of the projectile. These rocket motors provide additional flight energy to the shell, increasing its range (though decreasing the round's accuracy). Though the Navy does not yet have such shells, they are planned for future systems. The design team initially conducted its design analysis for Naval 5 inch shells (as will be discussed), but included the rocket assisted propulsion unit (RAP) in the architecture. The team's intent was that future versions of the WASP would be modified to allow the use of the RAP, thereby increasing WASP's range.

Flyer

The final primary element of the WASP system was labeled as the flyer. This element of the design would carry the sensor payload, conduct the cruise and loiter portions of the flight, enable mission retasking, and carry communications equipment. The flyer would also be the element equipped with the self-destruct mechanism as it would be the element of the design actually conducting the mission over enemy territory. On most figures generated by the design team, the flyer was often drawn with an airplane-like configuration. This representation, however, was for communications purposes only and did *not* represent the intended configuration of the vehicle. The point was that whatever form the vehicle eventually took, it would have to perform the functions listed above.

External Elements

Gun Systems

The most obvious of the external elements in the WASP design were the gun systems, the Army's 155 mm artillery guns and the Navy's 5 in. ship-mounted cannons. WASP would be fired from these weapons, so they constituted an important external system interface.

Global Positioning System (GPS)

Though not a definite part of the design at this point in the process, the team considered it likely that WASP's navigation systems would make use of the Global Positioning System, due to the navigational accuracy the system permits. To use GPS would require that WASP be able to receive the GPS signal from GPS satellites, hence the inclusion of the satellite as an external element. The design team would not be able to modify any of the GPS elements, but WASP would interface with them and make use of their functions (if the system were used in WASP's navigation systems).

Communications Satellite (Comm Sat)

The comm sat was included in as an interface as a possible means of achieving beyond line-of-sight communications between the WASP flyer and ground station and remote terminals. Like GPS, the team was not certain that WASP would use communications satellites, but they were listed as an external interface to keep the team thinking about their use. Also, like the gun systems and GPS, the team would only make use of the functions offered by existing communications satellite systems, and could not, therefore, modify such systems.

Taken together, the elements described above established the top-level systems architecture for the complete WASP system. This architecture could be thought of as a skeleton for the design -- it provided the initial framework around which more details of the design could be established and which could be used to assign work throughout the team. Prior to commencing this next phase of design, the system's requirements had to be refined, incorporating details from user feedback and derived requirements from the requirements and functional analyses.

4.5 Refined Systems Requirements

As discussed above, many of the initial requirements for WASP had a large range of possible values. The loiter time, for instance, was specified as 1 to 8 hours. From an aerodynamic point of view, each end of that range might have required very different designs. A major goal of the team, therefore, was to limit the range of these values.

This limiting process relied on several important factors. The first of these factors was a comparison of our system's projected capabilities and mission requirements to those of other UAV systems. From a marketing point of view, the goal of the refined requirements would be to identify a market niche in which WASP would offer advantages over other systems. Another important tool in refining the requirements was the projected capabilities of WASP. Through the process of analyzing the requirements, deriving system functions, and generating a top-level architecture, the team had gained a better sense of what were realistic and unrealistic capabilities. This knowledge would assist the team in narrowing the requirements. The final factor considered in deriving the refined requirements set was the feedback from the operational community -- the users. They would be the ultimate customers for our product, so their input was strongly valued.

Figure 4.11 shows a comparison of several current UAVs in terms of their endurance (e.g., loiter) times and mission ranges. Also shown in this chart are four possible locations for WASP, based upon the various mission scenarios originally considered. As can be seen, three of the four points place WASP in regions very near existing systems (endurance times and ranges of 6 hours and 75 kilometers, 1 hour and 200 kilometers, and 8 hours and 200 kilometers). The only point somewhat removed from the other systems is the mission requiring a loiter time of about an hour and a range less than 50 kilometers. Such a mission would most likely be one along the lines of company level reconnaissance as previously described. This simple chart, therefore, helped in narrowing two of the requirements: range and loiter time. This comparison provided the first indication that the lower end of each of these requirements (1 hour and 75 kilometers) would limit the degree to which WASP would have to compete with other systems.

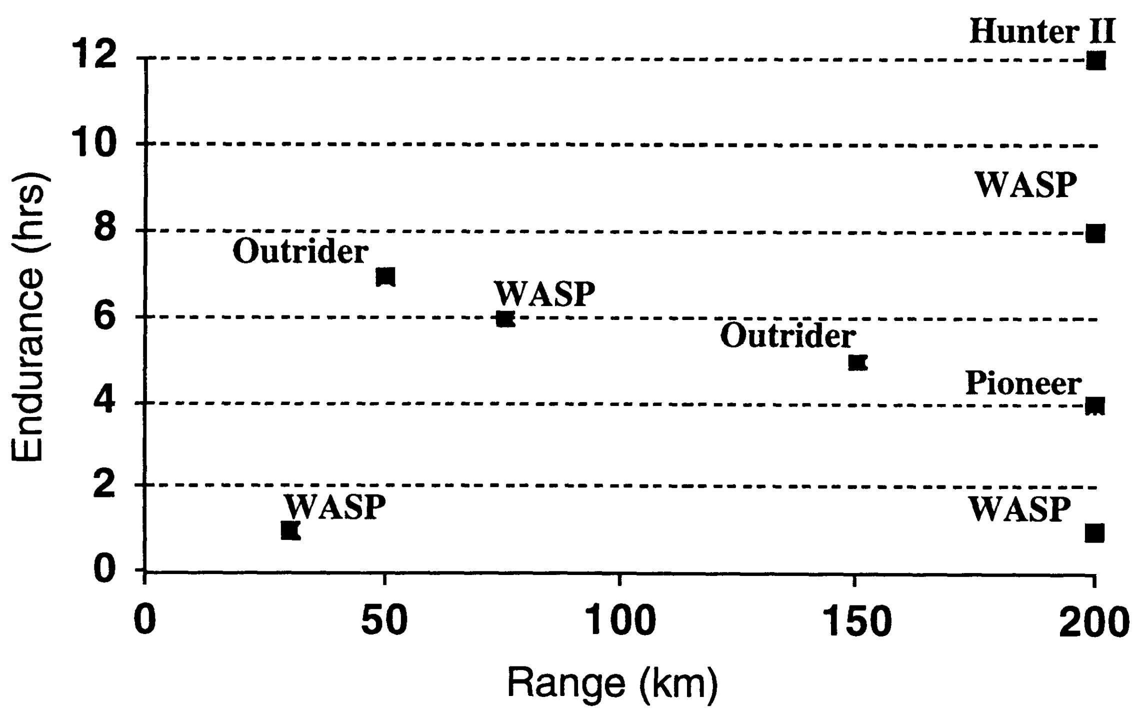

Figure 4.11 Comparison of Ranges and Endurance Times for Various UAVs and Potential WASP Missions

Supporting this tendency toward the low end of these requirements was information gathered about existing gun systems. Current Army and Navy guns had ranges of about 25 kilometers for simple ballistic projectiles and 50 to 75 kilometers for RAP projectiles (currently used only by the Army). For WASP to achieve a 200 mile range, therefore, would require the vehicle to carry a large amount of internal fuel and incorporate an efficient aerodynamic design. While the need for an efficient aerodynamic design did not worry the team, the need for a large amount of internal fuel did. These worries made the team be even more inclined to lean toward the short range, short duration mission types.

Another system limitation that began indicating a short range mission was the payload limitations of the WASP concept. Both the Navy 5 inch shells and the Army 155 millimeter shells are quite small compared to most operational UAVs -- WASP will not weigh more than 70 pounds (the mass of a standard 5 inch shell), while the Outrider UAV, for instance, weighs about 480 pounds. To ask WASP, therefore, to perform the same missions as these larger vehicles seemed to be somewhat unrealistic. Larger vehicles could fly farther, stay on station longer, and carry a larger payload. Thus, for overall performance, the odds seemed to be stacked in favor of these larger systems. If WASP were to have a competitive market advantage, it could not be in competition for the missions of these larger vehicles.

Returning again to the capabilities of the gun systems, the niche seemed to become clearer still. The advantage offered by being fired from a gun as compared to flying to a target area on a small engine (like other UAVs do) is speed. A five inch gun round can travel nearly twenty kilometers in under sixty seconds. A more conventional UAV would take much longer to arrive on station. This advantage in speed was also seen in the operational scenario of the WASP concept. Its requirements explicitly called for the system to be easy to use, and emerging design concepts from the team kept that in mind. In addition to a short flight time, it appeared WASP would also be able to be designed to have a very short preflight time -- on the order of minutes.

Finally, WASP was intended to be controlled at the small unit level: if a company commander needed to know what was beyond the next hill he could simply call his supporting artillery unit and request a WASP mission. Such direct support of the warfighter was in contrast to current systems, which rely on the one unit which controls the UAVs to disseminate their intelligence information to other units. Thus WASP would provide the opportunity for small unit commanders to more directly control the targets viewed by a reconnaissance vehicle. These quick response capabilities -- in terms of direct user requests, rapid mission planning, and short flight time to target -- were viewed as a major competitive advantage of WASP over other vehicles.

The utility of information from the user community in refining the requirements varied significantly (see Appendix C for details). On the one hand, users were interested in as much performance as possible, i.e., fly as far as possible, take images over as large an area as possible, and stay on station for as long as possible. While perhaps technically feasible to deliver a vehicle doing as much of all of these as possible, it was very unlikely that such a would vehicle meet WASP's cost constraints. In fact, some of the feedback we received indicated that our required price range might actually be too high. Members of the Defense Airborne Reconnaissance Office (DARO), for instance, suggested that to be used in the short range mission, WASP would probably have to cost about $2,000 to $3,000 per vehicle, an order of magnitude cheaper than originally specified. The reason given for this very low cost was the feeling that if WASP was used at the company level or below, it would be used in very large numbers. To be acquired in large numbers would require a low unit cost. DARO did agree, however, that this short range mission niche was the proper area in which to focus our attention, a feeling supported by other members of the operational community.

Members of the armed forces also provided valuable feedback in terms of the sensor systems for WASP. As mentioned previously, users tended to suggest they wanted as much as possible -- in the case of the sensor, that meant the highest resolution possible, transmitted in real-time. Again, while such capabilities were technically feasible, the team feared that meeting such goals would make the system extremely expensive. What users did suggest was that the system should have a resolution of at least 1-meter to be operationally useful. In addition, while real-time image transmission was highly desired, most users stated that they would be happy with one image sent every few seconds or possibly every few minutes. The driver for information timing was that the images be spaced so that moving objects would not disappear from the sensor's field of view between images. As long as an image was sent every minute or so, however, this requirement would probably be fulfilled.

Based upon all of the factors cited above, the following modifications were made to the original requirements:

- Range: Defined as the distance from the point of launch to the area to be reconnoitered. The range for WASP was set equal to the range provided by the ballistic cruise of the projectile (about 15 to 20 kilometers without RAP). WASP would not be required to cruise beyond this point to the target area.
- Loiter Time: Goal of an hour, but required to be at least 20 to 30 minutes.
- Operational Time: Equal to the loiter time.
- Image Resolution: About 1-meter. The ability of the team to meet this requirement would be highly dependent upon finding a suitable sensor.

- Information Timing: One image every few seconds, but the system did not need to transmit full-motion imagery.
- Cost: A new goal of $2,000-$3,000 per vehicle was established.

All other requirements for WASP remained unchanged. Together with the above modifications, the system requirements were fixed for the next phase of the design process. At the end of that process, however, the vehicle's performance would be compared to the requirements, and, if necessary, the requirements might be modified to be more in line with what was technically feasible.

While such a strategy of requirements-design-requirements revision might seem like "moving the goal posts to ensure the ball goes in" it was a process that was appropriate for the unprecedented system being designed. WASP was intended to have capabilities unlike any existing system. Since no present systems can do what WASP was meant to do, it was initially difficult for realistic requirements to be set. In addition, this project is not an acquisition program -- it is a technology development project. The goal of the project was not to meet some exact requirement but to demonstrate what might be feasible. Thus the results of this work could be used in the future to develop firm requirements for an operational system. At that point, a contractor could be held responsible for meeting the requirements, which would now have some proven foundation.

4.6 Assigning Team Responsibilities: The Work Breakdown Structure (WBS)

The above discussion has focused on *what* the team was doing. Almost as important, however, was the manner in which the team was accomplishing its tasks -- *how* the team was doing things. As will be shown, the team approached the design process in a manner that borrowed from current industry practice but that retained a great deal of flexibility to address unexpected issues or concerns. Given the number of people available to the design team and the time constraints of the project, proper management of these human resources proved a key aspect of ensuring that the project remained on schedule.

4.6.1 IPTs and Project Design Teams: Motivation for the WBS

Many contemporary engineering firms make use of a matrix organizational arrangement[8]. Such an organization is divided into specialty engineering groups, such as aerodynamics, structures, controls, manufacturing, etc. When the company receives a contract for a project, an integrated product development team (IPT) or project design team is formed. This team will draw engineers and experts from each group, establishing a project team that includes specialists from all of the necessary disciplines.

The motivation for the creation of the teams is to enable the company to effectively address problems of complexity. Modern engineering problems are too complex for one person to possess all of the knowledge needed to solve the problem. The goal of an IPT or similar design team is to create an environment in which the team can act as a "super engineer." By pooling the collective knowledge, skills, and talents of the individual engineers, the hope is that the team will possess all of the resources necessary to solve the problem and manage its complexity.

Our design team was faced with this same basic problem: no single person on the team possessed the knowledge needed to design the WASP system. The team, therefore, chose to implement a project design team approach. The first step in this process was to identify the needed specialty areas. This identification process was based on the top-level architecture. The architecture showed the basic system elements which would be needed, and, therefore, indicated the needed engineering specialties. Members of the team were then assigned to each specialty based simply on personal interest, so long as no specialty area became over-represented or under-represented.

Note that this arrangement did not constitute a true IPT since it did not include a manufacturing specialty. The fundamental concept, however, of using a teaming arrangement was inspired by the success of IPTs.

4.6.2 WASP Work Breakdown Structure

Table 4.5 shows the work breakdown structure (WBS) for the design team. As shown, the team divided itself into eight focus areas, each with a well-defined area of responsibility.

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[8] Jeffrey O. Gady, *System Integration*, Boca Raton: CRC Press, 1994, p. 34.

Table 4.5 Work Breakdown Structure

Focus Area	Members	Architectural Elements	Responsibilities
Mission/Architecture/ Configuration (Program Integration Team)	Bernard Asare Josh Bernstein Cory Hallam	1. WASP (Top Level Integration)	Vehicle Configuration Management Mission Profile Development Mission Requirements Development and Tracking System Performance Tracking (MOEs) Component Deconfliction Schedules Audits and Budgets (Power, Volume, Weight, MOEs)
Flyer Aerodynamics	Dave Iranzo	1.1.2.5 Flyer Aerodynamic Control System	Aero-Propulsive Analysis/Trades Aero-Propulsive Configuration Refinement Aerodynamic Computer Modeling/Simulation Aero-Systems Deployment
Flyer Propulsion	Ted Conklin	1.1.2.4 Flyer Propulsion System 1.1.2.9 Flyer Subsystem Power System	Aero-Propulsive Analysis/Trades Aero-Propulsive Configuration Refinement Engine Requirements and Selection Systems Power Requirements Development Power System Design/Selection
Communication Systems	Margarita Brito Matt Burba	1.1.2.7 Flyer Comm. System 1.2.1.2 Ground Station Comm. Sys.	Establish Comm. System Performance Requirements Comm. System Design/Architecture Antenna Placement/Deployment on Flyer Ground Station-Flyer Communications
Navigation, Flight, and Mission Control Systems	Vlad Gavrilets	1.1.2.6 Flyer GNC System 1.1.2.7 Flyer Comm. System 1.2.1.2 Ground Station Comm. Sys. 1.2.1.4 Mission Planning Sys. 1.2.1.5 Ground Station Flyer Control Sys.	Mission Planning Software Design Flight Control System Software Design Sensor Control GPS/IMU Integration Aerodynamic Computer Modeling/Simulation
Ground Station	Tan Trinh	1.2.1 Ground Station (All subsystems)	Ground Station-User Interface Design Ground Station-Flyer Integration Ground Station Computer Simulation
Sensor Systems	Tan Trinh	1.1.2.3 Flyer Sensor System	Sensor Requirements Development Sensor Selection Sensor-Flyer Integration
Shell Design and Integration	Cory Hallam Staci Jenkins	1.1.1 Shell (All subsystems) 1.1.2.1 Flyer Shell Interface Sys.	Shell Ballistic and Aerodynamic Analysis Shell Design Shell-Flyer Interface Design

The WBS indicated three aspects of each focus area. First, it showed which teams members had been assigned to each area. These assignments would be important later in the design process as new design issues came up that had to be addressed. The WBS provided a logical means for assigning such work. Second, the WBS referenced back to the architectural block diagram. (Note that the numbers in this column correspond to the element labeled in Figure 4.9.) The systems architecture had inspired the initial development of each focus area, so it was natural to refer back to these elements in the WBS. Finally, the specific responsibilities of each focus area were listed in greater detail, again aiding in the assignment of tasks and helping to show how each focus area would have to interact with the other areas.

4.6.3 Tracking Team Workload

Another tool for tracking the team's workload was developed from the WBS later during the project, at the beginning of the concept generation phase (see Section 6). Though presented out of chronological sequence, this tracking tool is discussed here due to its relationship to the WBS.

The tool is shown in Table 4.6. As can be seen, the tool lists many of the components of the WASP system (which were identified by the team later in the design process) down the left column. Across the top row are the names of all of the team members. "X's" indicated that a team member had responsibility for the item in that row. Thus, by looking down a column, the table provided a quick estimate of the number of different design elements for which a team member was responsible[9]. The table also provided a rough estimate of how much effort the team as a whole was devoting to a given design element by looking across a row. This table provided a valuable and easy to use method for ensuring that all aspects of the design were being addressed and that no single team member became too heavily loaded.

Table 4.6 Team Workload Tracking Table

	Individual Responsibilities									
COMPONENT	***Matt***	***Ted***	***Cory***	***Dave***	***Josh***	***Tan***	***Vlad***	***Margarita***	***Staci***	***Bernard***
Sensor						x				
Comm. Antenna	x							x		
Comm. Processor	x							x		
Motor		x								
Propeller		x								
Battery/Fuel		x								
Power Distribution & Conditioning		x								
FCS Sensors				x						
FCS Actuators				x						
"Mission" Processor							x			
Diagnostics System Processor							x			
Wiring		x								
Other Cabling										x
Wing Design				x						
Control Surface Design				x						
Self-Destruct Mech.			x							
Comm. Architecture	x							x		
Target Recog. & Image Processing	x				x	x	x			
Structural Design			x						x	
System Architecture Development			x		x					x
Shell Design & Shell-Flyer Interfacing			x						x	
Ground Station										
Interface Design			x							x
Budgets & Audits (Cost, Power, Volume, Weight, MOEs)					x					
Team Coordination				x	x					

[9] Note, however, this did not necessarily provide an accurate indication of a team member's workload -- some items in the table required significantly more effort than others.

5. Program Risk and Technical Challenges

5.1 Understanding and Defining Risk

The Random House Dictionary defines risk as "exposure to the chance of injury or loss; a hazard or dangerous chance"[10]. Based upon this definition, there are two major components to risk: the chance of being exposed to harm, and the harm, or consequence, itself. These concepts can be readily applied to engineering. When a design team undertakes a new project, they are often faced with many risks: there may be uncertainty as to whether or not a new technology will function properly, the product may call for very high levels of performance, or the team may have a highly constrained schedule. Any of these factors might jeopardize the team's ability to complete the project. The untried technology might fail, the desired levels of performance may not be achievable, or the team may simply run out of time. The consequences of any of these factors are about the same: either the project fails to achieve some of its goals, or, in the worst case, the project may completely fail.

In engineering endeavors, therefore, it is important for engineers to be aware of the risks faced by their project. If one is aware of the hazards one may face in the future, one may attempt to avoid them entirely. If the hazards are unavoidable, by identifying them early, one may at least prepare effective strategies to cope with, or manage, these problems. The notion of risk management has arisen from this concept of identifying potentially risky elements in a project. Again referring to *The Random House Dictionary*, risk management can be defined as "the technique or profession of assessing, minimizing, and preventing accidental loss to a business, as through the use of safety measures, insurance, etc."[11]. Risk management, therefore, has three components: assessing or identifying potential risks, attempting to minimize the consequences of the risks, or, even better, preventing the consequences from occurring at all.

One important aspect of risk management is that it is an ongoing, iterative process. Risk should be assessed at the very beginning of a project to identify projected future hazards. As a project progresses, however, the risks may change. Things that one believed would prove difficult may turn out to be easy while other elements that one expected to be simple may prove impossible.

[10] *The Random House Dictionary of the English Language, 2nd Edition, Unabridged.* Stuart Berg Flexner, ed. New York: Random House, 1987. p.1660.

[11] Ibid.

Thus it is important that the process of managing risk -- identifying risks, planning to cope with risks, taking preventative and corrective actions -- be repeated throughout the life of an engineering effort. Failing to take these actions can compound the consequences of failure faced by any design team working on an unprecedented system.

5.2 Risk Assessment Overview

As described above, it is important for a design team to be aware of the risks it will face during its project. This statement was as true for the MIT/Draper design team as it was for any other engineering effort. Our design team implemented a highly structured method of risk management for the project. This method is shown in an interaction diagram in Figure 5.1.

	Develop System/Subsystem Alternatives	Define Risk	Assess System Risk	Identify Highest Risk Systems Elements	Develop Risk Management Plan	Develop Design	Reassess Risk
Develop System/Subsystem Alternatives			x				
Define Risk			x	x	x		
Assess System Risk				x			
Identify Highest Risk System Elements					x		
Develop Risk Management Plan							x
Develop Design							x
Reassess Risk	x	x	x		x		

Figure 5.1 Interaction Diagram for the Risk Assessment Process

As can be seen from the interaction diagram, the first step in the risk assessment process was to develop alternatives for the various systems and subsystems of the vehicle. This design phase was a necessary first step because these initial "design points" served as "first guesses" for assessing the risk of the project. For instance, initial research into possible sensor options for WASP revealed that there was only one imaging camera that had been hardened for a high-g environment. Such information was extremely important to the design process, contributing to the high risk ranking that was placed on the vehicle's sensor system (see below).

In parallel to developing these design alternatives, the team also developed its working definitions of risk for the project. These definitions would then be used to rank the risk of each of the design elements being developed.

With design alternatives in hand and working definitions for risk set down, the team then moved into the heart of the risk management process. The first step in this process was to rank the degree of risk for each system or subsystem alternative. Once each element of the design had been so analyzed, a risk management plan was developed for each one. This plan showed how the team intended to develop high-risk elements so that they would eventually become low-risk elements (i.e., risk reduction), and also showed how the team had planned for fall-back options in the event that high-risk elements of the design proved unfeasible.

After going through this process, the team returned to conceptual design. The last step shown on the interaction diagram in Figure 5.1, then, denotes the iterative nature of the risk management process: reassess risk. After moving through a more detailed design process, the team would again revisit its risk planning, and repeat the assessment, incorporating the knowledge that had been gained during the design process.

5.3 Developing Subsystem Alternatives

As noted, prior to implementing any sort of risk management plan, it was necessary to develop a set of potential alternatives for each element of the design. To do so, each specialty group conducted background research in their respective fields, and then, based upon this research, the groups then derived several design alternatives. Following are brief descriptions of these alternatives[12].

5.3.1 Deployment Scheme

Two system-level alternatives for the deployment of WASP were initially derived. The high-risk option was referred to as "Super Deployment" by the team, and is illustrated in Figure 5.2. As shown, the basic concept was to accomplish the needed deceleration of the shell by

[12] The reader is referred to the theses of the other team members for more detailed descriptions.

pitching the shell up while still traveling at supersonic speeds. As the shell climbed, it would lose airspeed, until all of its kinetic energy had been converted to potential energy. Near this point of zero velocity, the flyer would be deployed to go on with the mission.

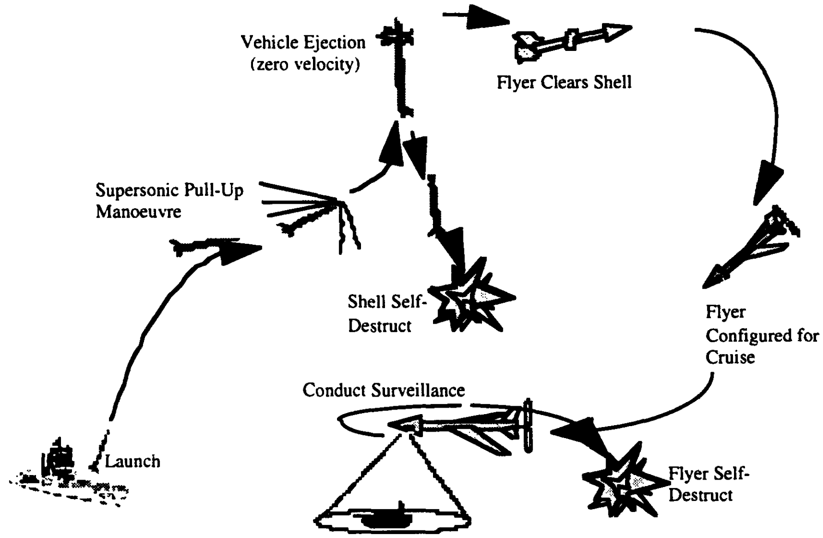

Figure 5.2 "Super Deployment"

The second design option developed for the deployment scheme was considered a much simpler design. Rather than deploying a flyer from the shell, the shell ejected a very simplified payload, consisting of only basic electronics, a sensor, and kept aloft by a parachute (see Figure 5.3). This design was considered a fall back option because it mimicked the operation of existing submunitions used by the military. This similarity to other systems could, the team believed, decrease the development risk of the concept.

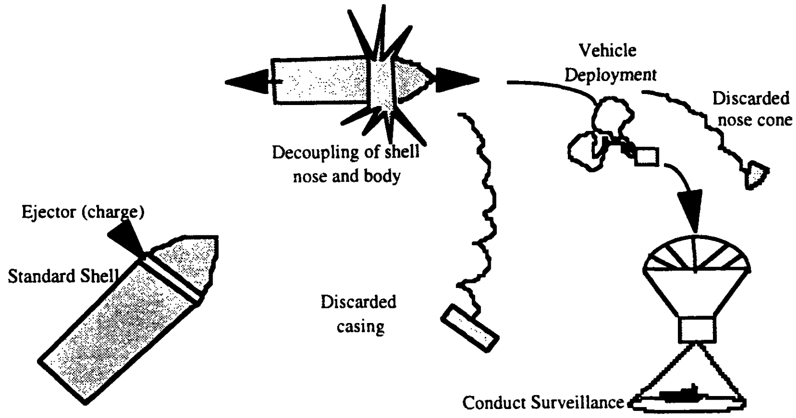

Figure 5.3 Fall-back Deployment Option

Initial calculations showed that little mission performance would be gained from the supersonic pull-up maneuver[13]. The team also did not want to be forced to such a simplified system as the fall-back deployment option suggested. Instead, the team adopted a parachute deceleration system, described further in Section 6.

5.3.2 On-Station Propulsion

The on-station propulsion unit would be used to achieve the required range and loiter time for WASP. The unit would have to be small and compact to fit within the shell, and would also need to survive the extremely high-g forces experienced by the vehicle when launched. A variety of options were initially explored to drive a propeller to provide thrust, including brushless electric motors, 2- and 4-stroke engines for remote control aircraft, Wankel rotary engines for remote control aircraft, a concept for a hybrid rocket motor, and a fly-wheel-based concept. Each of these alternatives had advantages and disadvantages in terms of performance, complexity, and projected g-hardening capabilities.

- The brushless motor was mechanically simple (a plus in terms of g-hardening), was expected to have a high efficiency and low vibration. Such a motor, however, would require a large power supply to provide the necessary run time (i.e., loiter time).
- The 2- and 4-stroke engines were appealing because of their widespread use on small remote control aircraft. The engines' capabilities were well-known, and the engines themselves would be cheap and easy to acquire. A potential drawback to these engines, however, was their

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[13] Cory Hallam, *MIT/Draper Technology Development Partnership Project: Aerodeceleration, Structures, and System Design of a High-G Rapid Response, Deployable Unmanned Aerial Vehicle*, Cambridge: MIT Press, 1997.

comparatively high number of moving parts -- it was expected that such engines might prove difficult to g-harden.

- The Wankel engine offered advantages in terms of its small volume-to-power ratio and its lower number of moving parts (compared to the 2- and 4-stroke engines). There were concerns, however, about such engines' reliability and its projected high fuel consumption.
- A hybrid rocket motor would offer the advantages of a high power density and high thrust-to-weight ratio. Such a motor would, however, require a good deal of new engineering and development (a threat to the project in terms of cost and time). In addition, though the motor would provide large amounts of thrust, it would only be able to generate this force for a very short time -- no longer than three minutes.
- The final concept was a flywheel that would make use of the forces generated during launch to wind itself. Once on station, a motor would then be connected to the flywheel to generate propulsion. The system's major advantage was that it would not require any other additional power sources. To develop such a system, however, was expected to be difficult.

Because of the overall performance offered by the 2-stroke engine, this option was selected for the flyer's propulsion system. The drawback of this system, however, was the potential difficulty that could be encountered in g-hardening the engine. The Wankel engine, therefore, was selected as a fall-back position in the event that the 2-stroke engine could not be g-hardened[14]. Still to be resolved, however, are details of the propeller design, including how the propeller will be deployed.

5.3.3 Power Unit

The power unit was the system which would provide power to all of the other systems on board the WASP flyer, such as the navigation computers, sensors, etc. As in the case of the propulsion system, a variety of options were initially developed:

- Thermal batteries were considered due to their proven high-g capabilities. The problem with such batteries, however, was their relatively low power density (between 10 to 30 W•h/kg), and short operating time (only a few minutes).

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[14] More details on the advantages and disadvantages offered by the various propulsion and power options can be found in Ted Conklin, *MIT/Draper Technology Development Partnership Project: System Analysis and On-Station Propulsion Design*, Cambridge: MIT Press, 1997.

- Common commercial batteries were also raised as an option for WASP. Such batteries have relatively good energy densities (50 - 150 W•h/kg), and are very inexpensive. The major concern with these batteries, however, was potential difficulty in g-hardening them.
- Fuel cells were considered due to their high energy density (approximately 200 W•h/kg) and high efficiency. The drawback to the cells, however, was their mechanical complexity.
- Another power option raised by the team was some sort of mechanical system, like a turbine connected to an electrical generator. While such a system has the potential to be efficient and generate sufficient power, it would also require a mechanically complex arrangement.
- Lithium batteries were the final option generated for on-board power. Such batteries have very high power densities (between 250 - 600 W•h/kg), but might prove difficult to g-harden.

It should also be noted that the team also briefly considered solar power for WASP. This option was ruled out fairly quickly, however, due primarily to operational concerns. Such a power system would constrain the flyer to operating in daylight and clear weather. Given that future versions of WASP's flyer would likely be used at any time day or night and in potentially bad weather, solar power was considered too constraining.

At the time of this writing, the team had selected a power subsystem for the flyer. During preliminary design, space had been set aside for batteries in each flyer concept. A specific type of battery and the associated power distribution system, however, had not been selected.

5.3.4 Guidance, Navigation, and Control (GNC), and Autonomy

The requirements for WASP stated that the vehicle had to incorporate some level of autonomous operation. To that end, three options were developed for the flyer.

The simplest version was based on a one-way datalink from the flyer to the ground station. The vehicle would fly a preprogrammed search pattern that could not be updated once the system was launched, and would send back camera imagery tagged with position information. This image transfer would constitute the only communications between the flyer and the ground station.

The next more complex design would function in basically the same manner as the first. In addition to the functions described above, however, the flyer would be intelligent enough to selectively transmit imagery, i.e., rather than sending back every photograph it took, the vehicle would only transmit those it felt contained objects or scenes of interest to the user. In addition, since the vehicle would be equipped with a significant amount of vision processing equipment, this version of the flyer would also have the ability to make use of vision-based navigation (navigating based on recognized landmarks).

The third and final system configuration developed for WASP was a two-way datalink. This arrangement would allow for continuous communication between the flyer and a ground station, and would allow for the flyer's mission program to be updated in-flight. In addition to allowing for changes in navigation, a two-way datalink would also allow for the user to take snapshots on command, rather than being limited to the preprogrammed picture-taking routine used in the first two options. Either the high degree of vision processing or the lower degree of processing described above could be used in conjunction with the two-way datalink.

The team eventually chose to pursue the two-way datalink arrangement. Such a configuration offered the greatest flexibility to the user and, therefore, seemed to best address the needs of the customer. The team did decide, however, to forgo any object recognition system for the vehicle, due to the complexity and developmental nature of such systems.

5.3.5 Sensor

Two basic options were considered for the sensor system for WASP. The first was to integrate an existing high-g camera system into the vehicle, while the second was to use an existing camera but then harden it to withstand high-g's. Two sensors for each option were identified.

In terms of existing sensor systems, the design team considered an imaging camera being developed by Xybion and the infrared seeker being used in the Precision Guided Mortar Munition (PGMM), a new weapon being developed by the US Army. The Xybion camera fulfilled the requirement for an imaging camera, but the system is still in development. Since it is still being developed, there is some of risk associated with using the camera. The PGMM sensor seemed to be more developed, but it had two disadvantages. The first was that it was an infrared system -- the requirements for WASP stipulated an imaging camera. Second, and more importantly, the PGMM sensor only had good resolution at very close ranges. It was feared that at the altitudes at which WASP would fly the sensor would not be able to resolve anything of interest.

Two additional options were considered if the team chose to g-harden a camera. The first was to purchase on off-the-shelf micro-camera and then attempt to g-harden it. The second was to adapt a micro-UAV imaging camera being developed by MIT's Lincoln Laboratory. Both of these options were considered fairly risky, since the team had limited experience in g-hardening optical systems.

Eventually the team decided to not directly address the sensor selection issue. As will be discussed, rather than attempting to acquire a g-hardened sensor or to g-harden an off-the-shelf system, the team designed a test plan that would allow for the use of a non-g-hardened sensor.

5.4 Defining Risk for WASP

5.4.1 Top-Level Risk Definitions

As discussed in the introduction to this section, risk can take on many forms: technological limitations, time constraints, performance, and cost limitations can all contribute to an engineering development program's level of risk. To manage this risk effectively requires that the different types of risk be well-defined. Such definitions aid in the risk assessment process by allowing similar risk factors to be grouped together, both within a given system or subsystem and between these systems or subsystems.

The MIT/Draper design team defined four top-level elements for system or subsystem risk: schedule, cost, technology, and performance. Each of these elements was defined as follows:

- *Schedule:* The chances and consequences of a project not meeting planned milestones at specified points in time.
- *Cost:* The chances and consequences that designing to target specifications and schedule will cost more than anticipated.
- *Technology:* The chances and consequences of a new technology not providing anticipated benefits within cost and/or schedule constraints.
- *Performance:* The chances and consequences of a new product (1) not performing to desired specifications, or (2) not including desired functionality with cost and/or schedule constraints.

There two aspects to these definitions that should be noted. First, all of the definitions include references to the two basic elements of risk -- the *chances* of a problem arising and the *consequences* of the that problem. Second, all of the top-level risk elements are inter-related. Performance risk is not simply the risk that a given system will not perform the desired functions; it is also the interaction between cost and schedule constraints that arise while attempting to design that level of performance into the system.

As will be described in the following section, these top-level definitions of system risk were supplemented by more detailed definitions used to assess the risk factors for each major system and subsystem considered.

5.4.2 Subsystem Risk -- Methods and Definitions

The risk assessment methodology used by the MIT/Draper design team had five basic steps. The first was to develop a metric which could be used to identify high risk elements in the design. This metric was then applied by each subsystem designer to his or her subsystem, generating a score for that subsystem's risk. The risk associated with each subsystem was then compared at a systems level, and then a list of the highest risk areas of the design was generated. Finally, the team generated fall-back options for each subsystem that was deemed to high risk.

The metric used by the design team was a risk factor based on failure and consequence indices. In this method, each subsystem was assessed in terms of its probability for failure -- the failure index, FI -- and the consequences should such a failure occur -- the consequence index, CI. The risk factor, RF, for the subsystem was then calculated as[15]:

$$RF = [(FI) + (CI)] - [(FI)x(CI)]$$

If a subsystem had a high risk of failure and the consequences of such a failure were significant, the subsystem was considered high risk. This relationship between the failure and consequence indices is shown in Figure 5.4.

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[15] Note that in the limit of either the FI or the CI going to one or zero, this formula will simply return the other value.

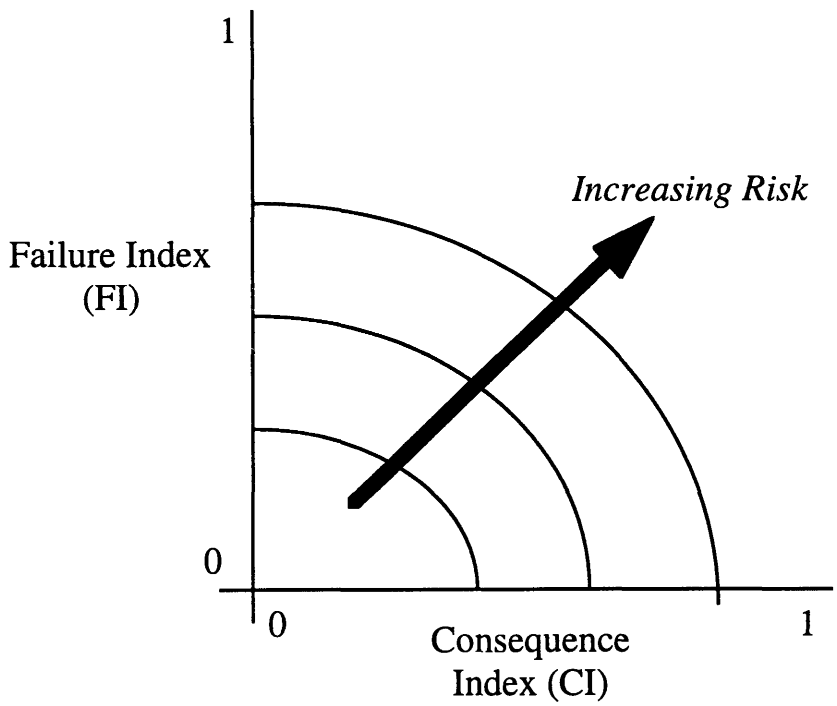

Figure 5.4 Relationship between Failure and Consequence Indices

To calculate the risk factor from the CI and FI, each subsystem was assessed in seven areas. Each of the seven areas was scored based on five possible levels: low risk (0.1), minor risk (0.3), moderate risk (0.5), significant risk (0.7), or high risk (0.9). The failure index was then based on the average score of a subsystem in the following five of the seven areas: maturity factor for hardware, maturity factor for software, complexity factor for hardware, complexity factor for software, and dependency factor. The consequence index was based on a subsystem's average score in terms of its technical factor and its schedule factor. The team would have liked to have included a cost score in the calculation of the CI, but at this point in the design process, the team did not have such data available. Table 5.1 shows a summary of these factors, along with how a score was defined.

Table 5.1 Scoring for Failure and Consequence Indices

Failure Index Scoring

Maturity Factor for Hardware

Existing	0.1
Minor Redesign	0.3
Major Change Feasible	0.5
Technology Available, Complex Design	0.7
State-of-the-Art, Some Research Complete	0.9

Complexity Factor for Hardware

Simple Design	0.1
Minor Increase in Complexity	0.3
Moderate Increase	0.5
Significant Increase	0.7
Extremely Complex	0.9

Maturity Factor for Software

Existing	0.1
Minor Redesign	0.3
Major Change Feasible	0.5
Technology Available, Complex Design	0.7
State-of-the-Art, Some Research Complete	0.9

Complexity Factor for Software

Simple Design	0.1
Minor Increase in Complexity	0.3
Moderate Increase	0.5
Significant Increase	0.7
Extremely Complex	0.9

Dependency Factor

Independent of Existing System, Facility, or Associate Contractor	0.1
Schedule Dependent on Existing System, Facility, or Associate Contractor	0.3
Performance Dependent on Existing System Performance, Facility, or Associate Contractor	0.5
Schedule Dependent on New System Schedule, Facility, or Associate Contractor	0.7
Performance Dependent on New System Schedule, Facility, or Associate Contractor	0.9

Consequence Index Scoring

Technical Factor

Minimal or No Consequences, Unimportant	0.1
Small Reduction in Technical Performance	0.3
Some Redunction in Technical Performance	0.5
Significant Degradation in Technical Performance	0.7
Technical Goals Can Not Be Acheived	0.9

Cost Factor (not used by WASP team)

Budget Estimates Not Exceeded, Some Transfer of Money	0.1
Cost Estimates Exceed Budget Estimates by 1% to 5%	0.3
Cost Estimates Increased by 5% to 10%	0.5
Cost Estimates Increased by 20% to 30%	0.7
Cost Estimates Increased in Excess of 50%	0.9

Schedule Factor

Negligible Impact on Program, Slight Schedule Change Compensated by Avaiable Schedule Slack	0.1
Minor Slip in Schedule, Some Adjustments in Milestones Required	0.3
Small Slip in Schedule	0.5
Large Schedule Slip	0.7
Significant Schedule Slip that Affects Segment Milestones or Has Possible Impact on System Milestones	0.9

5.5 Results of the Risk Assessment for WASP

5.5.1 System/Subsystem Results

The process described above was carried out for each of the major elements of the WASP design -- aerodynamics, communications, GNC and autonomy, power and propulsion, sensor, and deployment. Note that the aerodynamics and communications elements were not as well developed in terms of design as the other elements. These subsystems were scored based on the experience of the design team and some of the research that had begun in these areas. The results of the risk assessment are shown in Figure 5.5.

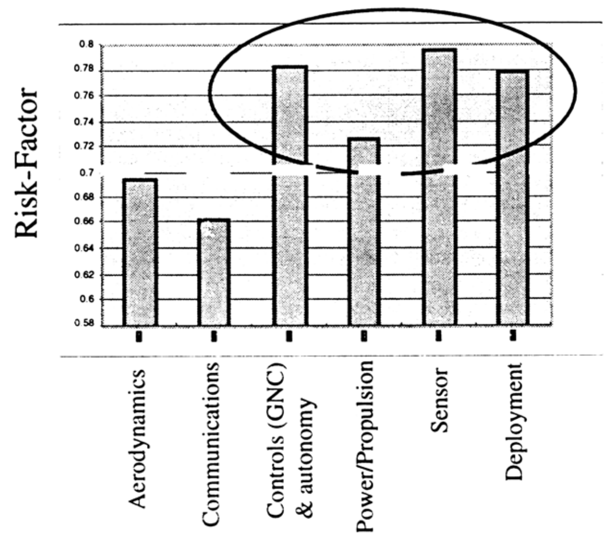

Figure 5.5 Risk Factors for WASP Design Elements

As can be seen from Figure 5.5, the highest risk elements for the WASP design at this stage in the design process were GNC and autonomy, Power/Propulsion, Sensor, and Deployment.

GNC and Autonomy was considered risky because of the most advanced option being pursued by the team -- the two-way datalink. This system design was, with little doubt, pushing the frontiers of modern UAV design. The design team was asking WASP to control its own flight attitude, navigate autonomously, and determine what photographed scenes would be of interest to its human controller. At the same time, the vehicle also needed to be capable of receiving updates to its mission plan, incorporating such updates, and then executing the new commands. The ability to accomplish all of these functions was then even more constrained by the small volume that would be available in the WASP vehicle. Taken together, these factors contributed to making the GNC/autonomy systems on WASP very risky.

The power and propulsion systems for WASP were also considered one of the high risk elements in the design at this stage in the development process. Two factors contributed to this result: the small volume of the WASP vehicle and the high-g environment at launch. Batteries did exist that could provide WASP and all of its systems with the required power for the necessary time. The two problems with most of these batteries, however, was that they would not fit inside the WASP flyer, and they would not survive the high g's encountered when the vehicle was launched. The propulsion unit faced the same two problems. Given that every system onboard the flyer would require power to operate, the consequences of this subsystem failing were quite high, hence its ranking as a high risk element.

The sensor was considered to be the design element with the highest degree of risk. This status resulted from several factors. First, like the power systems, sensors did exist that would accomplish the needed functions. Such sensors, however, either would not fit in WASP, would not survive the launch, or both. The only exception to any of these problems was the Xybion sensor, though it was not yet clear whether the sensor could be integrated into WASP. These problems were compounded by the key role that the sensor played in the WASP system. As previously discussed, the value of WASP was not derived from the vehicle itself, but rather from the information which it provided. The sensor, therefore, was a critical element of the WASP design -- should it fail, the vehicle itself would be virtually useless in its primary role, whether or not any of the other systems functioned properly.

The final element considered as high risk was the deployment scheme. While some existing systems provided some models for how deploy WASP, the design was not yet far enough along to say which ones might work well with our design. Should the deployment fail during an operational mission, the vehicle would be entirely useless. The deployment was, therefore, a critical step in the mission sequence. This criticality drove deployment to become a high risk element of the design.

5.5.2 The Technical Long Poles

To understand the results of the risk assessment at a higher level, i.e., in terms of the overall system, the team looked for trends in the causes of the risk for the high risk design elements. Based on this review, three major themes became apparent: the *constrained volume* of the WASP vehicle, the required level of autonomy, and the launch environment (i.e., high-g's) were increasing the risk associated with developing each subsystem. With these three factors identified, the team could move to address them more directly and from a systems point-of-view. For instance, by recognizing that volume was a major constraint for many of the subsystems, the team could examine the possibilities of removing some elements of certain subsystems to decrease their size. An early example of this concept was to remove any image processing capability from the WASP flyer and place it instead within the ground station. Such a relocation of functions would free up some volume inside the flyer while not sacrificing any functionality of the total WASP system. Similar trades were considered for the system's degree of autonomy. The goal of such trades was to lower the degree of risk associated with automated functions while at the same time not sacrificing total system functionality.

While design alternatives could be explored to cope with the problems presented by constrained volume and autonomy, those presented by the launch environment could not be so easily overcome. As will be discussed, the risks associated with the gun launch would drive much of the test planning done by the team later in the project.

In addition to these technical and design long poles, another long pole for the MIT/Draper team is the schedule. The design team is being asked to develop a functioning UAV prototype in less than two years, and not only is the UAV intended to have a high degree of autonomy, but it is to be fired from an artillery or naval gun. Such design factors would represent a major design challenge to any engineering firm, let alone the student design team. Like the problems associated with the gun launch, scheduling issues will come to play a large role in determining the final shape and form of the demonstration program planned by the design team.

6. Developing Architectures and Configurations

6.1 Design Process Overview

At this point in the project, the team had analyzed the system requirements, analyzed the system's functions, developed a top-level system architecture, and assessed the program's risk. The next step in the development process was to enter into the design phase.

This process is depicted in an interaction diagram in Figure 6.1. As the diagram illustrates, the first two steps of the architecture and configuration design process were to review the work that had already been completed regarding requirements and risks. Using the functional analysis, functions were first divided between hardware and software elements. Each function was then further decomposed, in the case of hardware elements, to the component level, and, in the case of software, to software modules and hardware. As this breakdown took place, new requirements were defined by the team for some of the software and for some of hardware components. At times these requirements related to new functions that had to be executed; other times the new requirements specified the nature of interfaces or system interactions.

Once the components were identified, the team revisited the system's architecture and used the components to develop architectural variants. These variants resulted in new interactions between system elements and the development of entirely new elements. In parallel with this architectural development, the team focused its energies on designing initial "aero-propulsive" configurations -- designing the flyer. These flyer designs were tightly coupled with the architectural developments, and the two design processes fed back to one another, as shown in the interaction diagram. In addition to feeding back to each other, the concurrent development of the architectures and configurations also fed back to every prior step in the process. This degree of feedback resulted because certain aspects of various designs would require new functions, which in turn generated new derived requirements, which then re-impacted the design.

	Review Requirements and Risks	Review Vehicle Functions	Identify Subsystem Components	Identify Subsystem Requirements	Develop Architectural Variants	Develop Configuration Variants	Develop Trade Study Criteria	Conduct Trade Study	Concept Downselect
Review Requirements and Risks	■		x		x	x	x		
Review Vehicle Functions		■	x		x	x	x		
Identify Subsystem Components			■	x	x	x			
Identify Subsystem Requirements				■		x			
Develop Architectural Variants	x	x	x	x	■	x			
Develop Configuration Variants	x	x	x	x	x	■	x		
Develop Trade Study Criteria							■	x	
Conduct Trade Study								■	x
Concept Downselect									■

Figure 6.1 Interaction Diagram for Architecture and Configuration Development

These iterative processes continued until several "final" architectures and designs were chosen. Once these final configurations were selected, the system requirements and functions were used to generate a set of trade study criteria. These criteria were then used to rank each concept, and then, based on the concept with the highest ranking, one was selected for further development. The downselect marked the end of this phase of the project.

6.2 Using the Resources of the Team -- Tiger Teams and Mini Teams

Until this point in the project, the team had been functioning using the work breakdown structure previously discussed. In this arrangement, team members focused their energies on addressing specific elements of the design. The development of architectural variants and flyer configurations was what could be termed a "highly integrative" process -- it required that the knowledge and creativity of the entire team be effectively combined to generate concepts which were responsive to the needs of each specialty group.

To effectively accomplish this integrative task, the team temporarily was reconfigured twice. The first of these reconfigurations moved the team away from the specialty groups into two Tiger Teams. Each team consisted of half of the members of the team, with members assigned in an attempt to provide a balanced set of skills and knowledge on each team. The task assigned to each team was simple in expression, but often difficult in execution: develop feasible architectural and configuration variants to meet the requirements set for the project, i.e., design WASP.

The Tiger Teams operated for about two weeks, developing a variety of different concepts. Only those pursued beyond the simple "back of the napkin" sketch will be presented in this thesis, however. Once the Tiger Teams had generated a total of three seemingly workable variants, the teams were disbanded.

With the disbandment of the Tiger Teams, the design team was divided into a new arrangement, this time into three Mini Teams. Each Mini Team included a third of the members of the design team, assignments to the teams again being made to ensure a balance of skills and knowledge across all three teams. One of the three concepts was then assigned to each Mini Team. The task given to each of the three teams was to develop the variant from a sketch to a refined conceptual design that incorporated initial component layouts and basic dimensions. This process lasted for about two weeks.

Once the Mini Teams had completed the conceptual design for each variant, they were dissolved and the specialty groups took over once again. Each specialty group was then responsible for conducting their respective analyses on all three designs -- the aerodynamics and propulsion groups assessed each design's aerodynamic and propulsion performance, the shell integration group reviewed how each flyer design would interact with the gun environment, etc. A final or preferred concept would then be selected from these analyses.

6.3 Architecture and Configuration Variants

Prior to entering into conceptual development for the system, one question which the team had to address was which gun system the initial design should represent: the 5 inch Naval gun or the 155mm Army howitzer or both. Since the 5 inch shell was smaller than the 155mm shell, this design would be the more constrained of the two. The team felt that so long as a vehicle that could be designed to fit in the smaller shell, it would be a relatively simple matter to increase the vehicle's size (either with a larger payload, more fuel, or batteries) to fill the larger Army projectile. The decision was made, therefore, to develop the initial concepts for the WASP flyer based on the Naval 5 inch Mark 54 projectile.

Several different architectures and configurations were generated by the Tiger Teams and three flyer designs were eventually considered by the Mini Teams. The details of the two designs which were not selected, a glider design and another design referred to as the Twin Shells concept, are presented in Appendix F along with some alternative system architectures. The concept which was selected, referred to as Supershell during its development, is described below in Section 6.5.3.

6.3.1 The Component Table -- An Important Integrative Tool

While the Mini Teams were refining their concepts, one important aspect of the designs was that they needed to execute the same basic system functions described in the baseline functional flow diagram. While the exact manner in which these functions were accomplished could vary, the fact that every concept addressed the same functions meant that there would be a high degree of commonality in the components used to design a flyer configuration.

To assist the team in incorporating both the necessary functionality and the components needed to achieve that functionality, the Program Integration Team developed a component table listing all of the components thought to be needed in any flyer design. An example of one of these tables is included in Appendix E. Many of the components were listed in several varieties (there were several different engines from which to choose, for example), while specific versions of components that had to be used were highlighted.

This massive table was updated throughout the design process, as additional component research was completed. This research at times resulted in additional requirements for a given component, or the addition of a new component, either as a variant of an existing component or in place of one. Several components identified by the team as necessary for each flyer could not be found in existing sources. In these cases, estimates were made based on other components with similar functions and engineering judgment.

The resulting table proved extremely useful to each Mini Team, and to the specialty groups later in the design process. The table was an attempt to ensure that all of the designs accomplished the necessary functions and included the required hardware. In addition, the table sought to guarantee that all of the designs were compared on a "level playing field." It could have been possible, for instance, for one team to assume that an engine with a specified power could be built at a much smaller scale than another team assumed. The availability of the table ensured that such assumptions were avoided during the design process.

6.4 Trade Study Methodology

With three configurations designed, the team now had to chose one to further pursue. To make this choice, the team followed a structured trade study approach. Criteria upon which to judge the designs were first created. The designs were then analyzed in terms of these criteria, and their scores compared. As the comparison process progressed, the team's understanding of the important criteria upon which to judge the concepts changed slightly, and modifications were made to the analysis.

Presented in the following sections is the final set of criteria and scores used to compare the designs. It is important for the reader to note, however, that the process was somewhat iterative. The design that was eventually chosen, however, was always the highest scoring design throughout all of the modifications made to the selection criteria.

6.4.1 Scoring Methodology

As described below, the team generated a set of criteria used to compare the vehicle concepts. To aid in the actual comparison process, a numerical scoring method was established. The steps of the method were as follows:

1. Selection criteria and their weights were established (see the next section for details on the criteria).
2. A baseline concept was chosen. This concept would serve as a reference against which the other concepts would be judged. Concepts with a score higher than the baseline's would be better, concepts with lower scores would be worse.
3. The actual value for each of the baseline's specifications were filled in next to the appropriate criterion. For example, one of the criteria was cost, so the cost of the baseline, in dollars, was entered.
4. All of the baseline's values were then divided by themselves to obtain a relative score in each category. Note that all of these values were now equal to one.
5. These relative scores were then multiplied by the weighting factors for each criterion, generating a weighted score.
6. The weighted scores were summed, resulting in a total score.
7. For each of the other concepts, the specified values for each criterion were entered, i.e., cost as dollars, range as kilometers, etc.
8. The values for each of the criteria for each concept were then divided by the corresponding specified value (with units) for the baseline concept to obtain a relative score.

9. The relative scores were then multiplied by the weighting factors in each category to find a weighted score.
10. The weighted scores were then summed to find the total score. The higher the total score, the better the concept.
11. Finally, a relative total score was calculated by dividing the baseline's total score into all of the total scores for the concepts (again resulting in a score of 1 for the baseline).

6.4.2 The Criteria

Prior to actually conducting the trade study, the team developed a set of the criteria to judge the designs. These measures were derived from two sources. The first source, and perhaps most important, was the customer's requirements. Many of the criteria were derived directly from measures the customer used to describe the value of the design, such as cost, loiter time, and range. Additional measures were then created by the team to address customer requirements which could not be readily measured and to compare features which the team felt were significant. An example of the former was the establishment of the "deployment scheme complexity" measure to derive a subjective measure of the expected reliability and difficulty of manufacture for the vehicle concepts. An example of the latter was the definition of the "inert mass fraction," used by the team to judge how large a payload the flyers could carry.

As noted, the criteria evolved somewhat during the evaluation process. Presented here are the final ones used to justify the team's final selection. The criteria were:

- *Cost:* A mid-range cost estimate for each vehicle was calculated and compared (see next section). Lower cost was considered better, therefore it was weighted as -10 (the greater the cost, the more negative the cost score, and the lower the total score).
- *System Complexity:* A subjective measure of the overall complexity of the flyer and its systems. The system complexity multiplier was -10.
- *Loiter Time:* The estimated loiter time in seconds for the operational vehicle. For analysis purposes, the loiter time was calculated between the altitudes of 1000m down to ground impact. This altitude range was selected because the team believed the camera would only be able to supply tactically useful information at these altitudes. Loiter time was weighted as 10 (longer times were better).
- *Inert Mass Fraction:* Used as a measure of the flyer's ability to carry a payload. This value was calculated as:

$$IMF = (M_t - M_p - M_f)/M_t$$

where M_t was the total vehicle mass, M_p was the mass of the payload (i.e., the sensor), and M_f was the mass of the fuel carried by the vehicle. The IMF was weighted as -8, i.e., the lower it was the better the design.

- *Surveillance Area:* Total surface area (in square kilometers) viewed by the sensor between the operational altitudes of 1000m to ground impact. This criterion was weighted as an 8.
- *Component Technology Availability:* This was a subjective measure used to judge whether or not all of the components needed for the flyer already exist. A higher score implied all of the necessary technology was available, a lower score implied development work would be required. The multiplication factor for this measure was an 8.
- *Deployment Scheme Complexity:* A subjective measure of the complexity of the deployment scheme for the flyer, it was weighted as -7.
- *Electrical Power Volume Available:* This value was used to measure how much volume would be available for the flyer to carry batteries, and, therefore, it gave some indication of how long the flyer's systems would be able to operate. This value was measured in cubic centimeters and was weighted as 7.
- *Lift-to-Drag Ratio:* A classical measure of the aerodynamic efficiency of a flying vehicle. This value's multiplication factor was 6.
- *Flyer Range:* The linear distance traveled by the flyer from 1000m altitude until it would crash into the ground[16]. Measured in kilometers, the weighting factor for the value was 5.
- *Loiter Time-to-Propulsion System Weight Ratio:* This criteria was originally included with the others to obtain some estimate of how efficiently the flyer was using its propulsion system. The ratio had units of seconds per kilogram of propulsion system weight. When calculated for the glider variant, however, this criterion had an undefined value (due to division by zero -- the glider had no propulsion system). Since such an answer was not particularly useful, the criterion was removed from consideration.

[16] Note that in an operational scenario, the vehicle would self-destruct at the conclusion of the mission. For purposes of this analysis, however, the team found it more convenient to calculate the range in terms of the longest distance the flyer could possibly achieve.

6.4.3 Trade Study Analysis Example: Cost Estimation

Cost was one of the most important needs for the customer, thus it was also important to include this factor as a criterion in the selection process. Cost is also a very difficult factor to estimate, and is in fact the subject of more than one research project at MIT. Given that the team was still at an early stage of the design process, cost was even more difficult to estimate. Though additional research could have been conducted to improve the cost estimates, there was little time to spend on such an activity (a result of the *risk* associated with the fast paced schedule of the project). A first order estimate was required, however, and this section details how that estimate was derived.

Three basic factors were used to estimate the cost of each vehicle. The first was the component cost, the cost for each of the major components used in the design, second was the structural cost for the vehicle, and the third was a subjective measure of the design's complexity. The component costs were based on prices taken from catalogs in some cases and from estimates provided by Draper in other cases. The structural cost for each concept was estimated from a baseline cost, multiplied by a weighting factor for each design. This baseline cost was taken as the estimated structural cost for Supershell. The structural cost estimate was assumed to include labor and assembly costs for the vehicle. The component and structural costs were summed, and then multiplied by the complexity factor to determine the total vehicle cost.

The collection of component cost data was the responsibility of each specialty group. The author was responsible for organizing the data and deriving total costs.

For all of the costs gathered by the team, an attempt was made to derive four estimates: a first example or prototype cost, then low, medium, and high estimates. The first example cost was intended to be the estimated cost for the construction of the first example of an operational vehicle. The remaining cost estimates were intended to account for economies of scale, i.e., the more vehicles produced, the lower the unit cost. In the event that a first example price was not available, the highest price given was used to estimate the total vehicle first example cost.

The following tables list the cost estimates for the three concepts.

Table 6.1 Component Cost Estimates

Component*	First Example	Low	Medium	High
Motor	-	-	140	-
Batteries	-	-	3500	-
Sensor	-	5000	7500	10000
Communications	4000	-	1000	-
Actuators (for two)	-	-	120	-
GNC System	105000	860	25000	50000

* For items such as the engine and batteries, where multiple options existed, an average cost was provided.

Table 6.2 Structural Cost Estimates

	Structural Cost Estimates				
Vehicle	Weighting Factor	First Example	Low	Medium	High
Supershell	1	100000	1000	4000	7000
Twin Shells	1.25	125000	1250	5000	8750
Glider	0.6	60000	600	2400	4200

Table 6.3 Total Vehicle Cost Estimates

		Total Vehicle Cost Estimates			
Vehicle	Complexity Factor	First Example	Low	Medium	High
Supershell	1.75	389830	20335	72205	125580
Twin Shells*	2.25	811170	36540	162045	288607.5
Glider	1	182620	11080	39520	68820

* All component costs for the twin shells concept were multiplied by two *except* for the cost of the sensor and the structure.

6.5 Trade Study Results

6.5.1 Selection Criteria Scores

The results of the selection criteria analysis are presented in Table 6.4. As can be seen by looking at the relative total scores, Supershell seemed to represent a better option than the glider, while the Twin Shells concept appeared to be significantly worse. To understand these final results, it is worthwhile to consider the criteria which lead to significant differences in the scores for each concept. These driver scores are circled in the table.

Supershell's higher total score was most dramatically affected by its high score in the surveillance area category and its range. Because of the inclusion of an engine in the design, Supershell's performance in both of these areas was significantly better than that of the glider.

The Twin Shells design was most dramatically affected by its score in three areas: cost, system complexity, and deployment scheme complexity. All of the high scores were a direct result of the complex system architecture used for the vehicle. The component technology availability score was a result of the need to include two of many components. Due to this duplication, the sizes of these components had to be even smaller than those in the other designs. The team had already determined that many of those components would have to be custom made, since items of the required sizes were not currently available off the shelf.

Based on the results of these scores, the Twin Shells design was discarded as a candidate concept. The team felt that the system's complexity, and corresponding added costs, did not offer advantages significant enough to justify attempts to deal with the complexity. The decision, therefore, had to be made between the glider concept and Supershell. To make this final judgment, the team supplemented the results of the selection criteria analysis with some additional factors.

Table 6.4 Selection Criteria Analysis Results

Measure	Units	Weighting	Glider			Supershell			Twin Shells		
			Numerical Value	Comparative Score	Weighted Score	Numerical Value	Comparative Score	Weighted Score	Numerical Value	Comparative Score	Weighted Score
Cost	dollars	-10	39520	1	-10	72205	1.83	-18.27	163045	4.13	-41.26
System Complexity	subjective	-10	4	1	-10	7	1.75	-17.50	10	2.50	-25.00
Loiter Time	seconds	10	830	1	10	1358	1.64	16.36	721.5	0.87	8.69
Inert Mass Fraction	-	-8	0.97	1	-8	0.98	1.01	-8.08	0.99	1.02	-8.16
Surveillance Area	square kilometers	8	19.5	1	8	48.2	2.47	19.77	34.8	1.78	14.28
Component Technology Availability	subjective	8	9	1	8	7	0.78	6.22	3	0.33	2.67
Deployment Scheme Complexity	subjective	-7	3	1	-7	5	1.67	-11.67	9	3.00	-21.00
Electrical Power Volume Available	cubic centimeters	7	198	1	7	259	1.31	9.16	144	0.73	5.09
Lift-to-Drag Ratio	-	6	22.5	1	6	19.9	0.88	5.31	19.9	0.88	5.31
Flyer Range	kilometers	5	19.9	1	5	58.1	2.92	14.60	37.7	1.89	9.47
				Total Score	9		***Total Score***	15.90		***Total Score***	-49.91
				Relative Score	1		***Relative Score***	1.77		***Relative Score***	-5.55

Note:
- The Glider variant did *not* have space for a self-destruct mechanism, so such a device was left out. This omission means that the design does *NOT meet all of the requirements for the system.*

6.5.2 Additional Decision Drivers

A team meeting was held to make the final decision regarding which concept to move into detail design and development. As noted above, the first decision that was made was to throw out the Twin Shells concept from discussion. To make the final decision between Supershell and the glider, the team was uncomfortable relying solely on the numbers yielded by the selection criteria scores. This hesitancy resulted from the approximate nature of all of the numbers used in the selection criteria analysis. The team wanted to ensure that even if these numbers changed (which was likely), their decision would still be justified.

After a significant amount of discussion, the team finally chose to pursue the Supershell concept based first on its score in the selection criteria analysis, supplemented by the following additional considerations.

- *Similarity to the Army's Concept:* One factor that harmed the chances of the glider design being further developed was its similarity to the Army's concept for such a vehicle. While this similarity was intentional and served as a useful basis for comparison with other concepts generated by the team, it did not seem particularly worthwhile to continue to pursue it. In the end, the MIT/Draper team would simply end up with a vehicle very similar to something the Army had designed on its own.
- *Design Flexibility:* A major advantage presented by the Supershell concept was the potential flexibility it offered compared to the glider. The glider design could not fit an off-the-shelf engine. To allow the installation of an engine in the glider would require the development of an entirely new propulsion system. Supershell, on the other hand, could fit an existing engine inside of its body. In a worst-case scenario in which component sizes increased over their projected values, Supershell could be converted to a glider design by removing the engine. The design would then be no worse off than the original glider design, plus it would still retain the unique "transforming" nature of the deployment scheme.
- *Requirements Fulfillment:* Supershell met all of the requirements set for the project. The glider, however, did not include a self-destruct device in the design, nor was it clear that such a device could fit. This omission meant that the glider design did not meet all of the requirements for the system.
- *"Unobtainium":* One of the original requirements for the entire project was that whatever system was developed by the team must include some elements of "unobtainium" -- the design must challenge existing technology. The team believed that Supershell, particularly with the

inclusion of a propulsion system, its transforming nature, and use of a composite shell, offered more "unobtainium" than the glider design.

Together with the results of the selection criteria analysis, the team felt fully justified in pursuing the Supershell design. This decision was then presented to the team's sponsors at Draper Laboratory, who concurred with the team's assessment.

6.5.3 Supershell

The basic arrangement of Supershell is shown in Figure 6.2. As mentioned above, Supershell was intended to be something like a "transformer." The motivation for this approach to the design was that such a configuration would maximize the internal volume of the flyer, allowing more room for components. With other concepts that relied upon storing the flyer inside the shell, a significant amount of volume was sacrificed to structure: the structure of the shell wall, plus the structure of the flyer itself. The goal of Supershell was to eliminate that duplication by making one structure perform both functions.

To further increase the volume available, and to reduce the weight of the flyer (an advantage in terms of aerodynamic performance), Supershell was also conceived with the intent that it be constructed from composite materials. The composites, it was hoped, would allow for a smaller wall thickness than would be allowable were the shell made from metal. This reduced wall thickness would then allow for a larger empty volume inside the shell which could be used to place components. Note, then, that this design was a direct attempt to address the risks associated with the small volume of the vehicle.

While the composite shell offered advantages for the flyer, it did pose some difficulty for the interaction between the vehicle and the gun systems with which it was intended to be used. These guns were all rifled, meaning that when a projectile was fired, the lands of the rifling would actually carve grooves into the shell's surface. A composite material would likely fracture under such loads[17]. To address this problem, a launch collar was conceived to fit around the Supershell during launch. As illustrated in Figure 6.3, once the system was ready to deploy, the collar would separate from the flyer, drifting to the ground on a parachute.

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[17] Cory Hallam, *MIT/Draper Technology Development Partnership Project: Aerodeceleration, Structures, and System Design of a High-G Rapid Response, Deployable Unmanned Aerial Vehicle*, Cambridge: MIT Press, 1997.

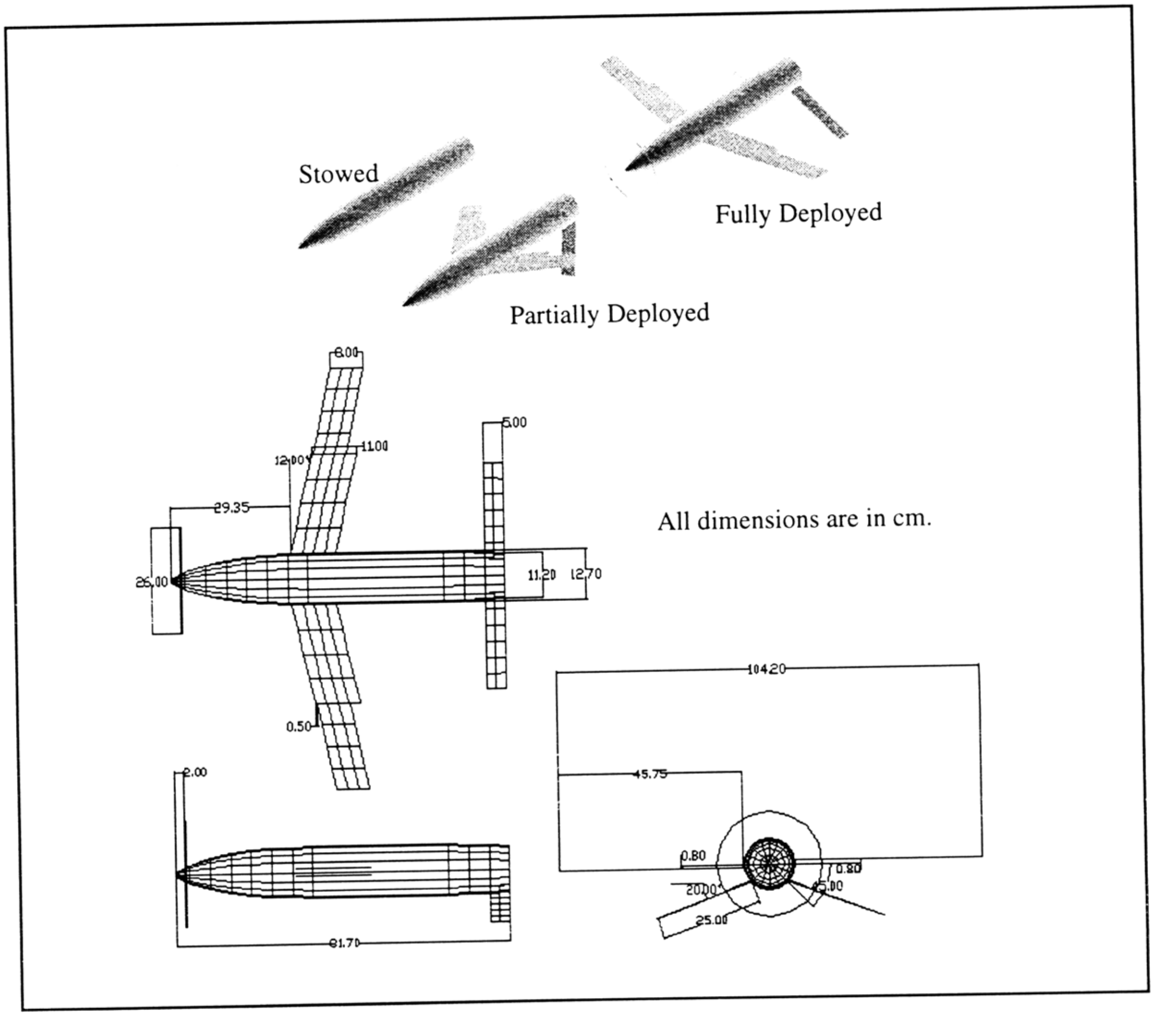

Figure 6.2 Supershell

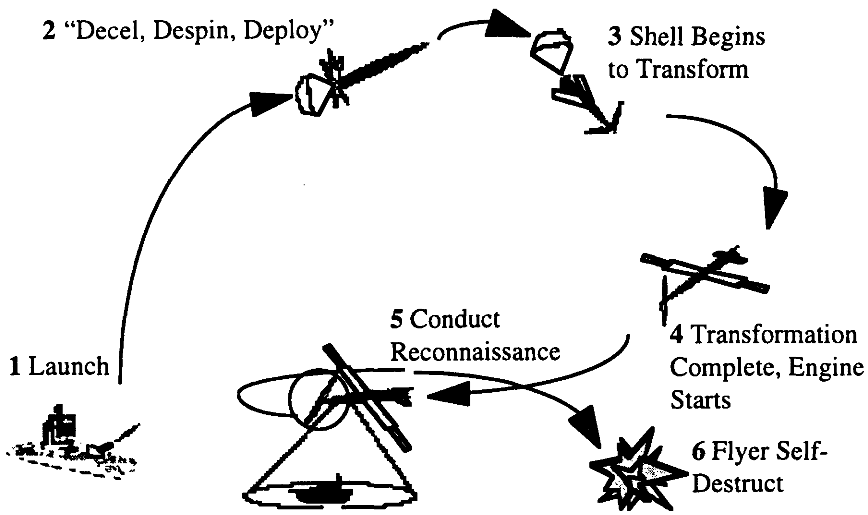

Figure 6.3 Supershell Deployment Scheme

At this point in the project, two parallel development paths were started. The first development effort, and the smaller of the two, was a refinement of the requirements, functions, and performance of an operational WASP system. This effort would ultimately lead to a preliminary design for the final vehicle. The second development effort, and the one in which the team focused a much greater portion of its energies, was the development of the demonstration program for the project. The following sections detail that planning.

7. Developing the Demonstration and Test Program

7.1 Demonstration and Test Plan Overview

7.1.1 Operational versus Demonstration Vehicle

With a concept now selected, the team had to address the issue of what the final deliverable of the project would be. What became evident to the team very early in these discussions was the ultimate deliverable would be a prototype WASP system rather than an operational one.

There were several factors which contributed to this decision. The first was component availability. Some the items that would be needed in an operational WASP system, particularly some of the g-hardened electronics, were still in development. While the items did physically exist, it would not have been possible for the team to acquire them. Another factor contributing to the decision to develop a prototype was the desire to avoid what could be called the "big bang effect." This effect is what occurs when one tries to assemble and integrate too many new systems all at one time -- inevitably the system will not operate properly. To avoid the big bang effect, a design must be developed sequentially, in small steps, until finally the entire system has been assembled. This process, is a time consuming one. To develop a fully operational system would simply have been too large an effort for the design team.

Instead the team chose to pursue a test program which would demonstrate the core concepts of the WASP system, without necessarily requiring that the entire system be developed to an operational configuration.

7.1.2 Demonstration Program Development Process

The interaction diagram for this phase of the project is shown in Figure 7.1. As can be seen, this process was composed of a set of highly interactive sub-processes, with many feedback loops. The process began with the identification of test plan goals and the identification of facilities and capabilities which would be available for the team to conduct testing. This process was then followed by the definition of the ultimate deliverables, i.e., the final product of the project. Once these deliverables were identified, they were decomposed. This process involved working backward from the ultimate deliverables to determine what subsystems should be developed and tested to ensure that the final products themselves would function as expected. Once these subsystem tests were identified, their relationships, that is, how the results of one test would impact another, were established on an Integrated Master Test Plan (IMTP). This plan also determined the schedule for the tests.

With an initial plan established, the design process was repeated, but this time it was carried out for the test elements. Functional flows were developed and then compared to the conceptual design and the test plan to ensure that the tests would demonstrate the necessary features. Detailed design and testing of the subsystems was then carried out, followed in turn by the detailed design and testing of the final, integrated test elements and ultimate deliverables.

	Identify Top-Level Goals of the Test Plan	Identify Test Facilities/Capabilities	Define Ultimate Deliverables	Decompose Ultimate Deliverables into Sequential Subsystem Tests	Develop Integrated Master Test Plan	Conduct Functional Analysis(es)	Review Conceptual Design	Conduct Detail Design of Subsystem Test Elements	Conduct Detail Design of Integrated Test Elements	Enter into Design/Development/Construction of Test Elements
Identify Top-Level Goals of the Test Plan	■		x		x					
Identify Test Facilities/Capabilities		■	x							
Define Ultimate Deliverables			■	x			x	x		
Decompose Ultimate Deliverables into Sequential Subsystem Tests				■	x	x				
Develop Integrated Master Test Plan					■	x	x			
Conduct Functional Analysis(es)		x		x		■		x	x	
Review Conceptual Design		x		x			■	x	x	
Conduct Detail Design of Subsystem Test Elements		x		x				■	x	x
Conduct Detail Design of Integrated Test Elements		x		x				x	■	x
Enter into Design/Development/Construction of Test Elements		x		x					x	■

Figure 7.1 Interaction Diagram for the Demonstration and Test Plan Development Process

7.2 *Defining the Goals of the Demonstration Program*

7.2.1 Top-Level Goals

At the highest level, the goal of the demonstration program was to demonstrate the design elements and integrated systems for an artillery gun-deployed unmanned aerial reconnaissance vehicle. Note that this top-level goal defined two elements for the testing program: design elements and integrated systems. The purpose of defining these two elements in the top-level goal was to clearly establish the incremental approach that would be used for the demonstration program. First, design elements, i.e., subsystems, of the system would be tested in stand alone modes. As the functionality of these lower-level elements was verified, they would be combined in incremental steps, building up subsystems form the component level. Once a subsystem was verified, it would be combined with others until a nearly fully functional vehicle was assembled.

7.2.2 Revisiting Risk; Implications for the Test Plan

As stated in section 5, a successful risk management plan will reassess program risk throughout the life of the program. To help design the demonstration plan, it was necessary to re-evaluate the risks associated with the project.

Several high risk elements were identified for the test plan: the high-g environment (in particular, the survival of mechanical systems in this environment), volume and surface area constraints due to the small size of the shell, the composite structure, and the deployment scheme. Three of these elements were carried over from the original risk assessment. The high-g environment, size constraints, and deployment methods were all initially listed as high risk aspects of the design, and there was no way to avoid them. The test plan, therefore, would have to address these specific issues. If the design team could not demonstrate how to overcome these risks, the WASP concept would not be viable. As will be discussed, these high-risk elements did in fact shape the entire approach to testing taken by the team.

Two additional elements of the design which were considered a priority for testing were the aero-propulsive design and the GNC and flight control systems (the autonomy systems). Though not considered as high risk as the design elements listed above, these aspects of the design were also essential for the WASP concept to operate successfully. Note that this classification as a lower-risk element was a change for the autonomy systems. This downgrading of the autonomy risk was due to the fact that the team had decided to do without advanced vision processing or object recognition. The autonomous systems would now only be responsible for navigating and controlling the vehicle in flight. Though not simple tasks, these were functions that had been demonstrated in other systems.

The vehicle's aerodynamics were never considered high risk design elements. Members of Draper Laboratory, however, felt that demonstrating that the flyer was controllable would be an important aspect of the demonstration program. The design did have some technical risk associated with it, in that the design basically attached wings and tails to an artillery shell to turn it into a miniature airplane. Thus the consensus throughout the team was that the aerodynamics of the vehicle should be tested.

7.3 Constraints on the Demonstration Program

The design team faced several constraints as it moved into the testing and demonstration phase of the project. One of the next most significant of these constraints was the availability of facilities to test the WASP design. Picatinny Arsenal was identified early in the demonstration planning as a likely location for many tests. The Arsenal has several air guns and a rail gun which can be used for high-g testing of components. The size of test elements that can be incorporated into the guns' test sections is limited, however. In addition to these size limits, the air and rail guns would not provide any means to allow for tests of the deployment system for the flyer.

In fact, the search for a method to test the deployment system in operation proved to be a major constraint to the development of the test plan. As will be discussed, a two-pronged approach was taken to address this issue: a flyer prototype that could be deployed from a small aircraft would be developed, and efforts would be made to find some means of conducting a field test of the system. The intent of the field test was to allow a WASP prototype to be fired from an actual gun and then demonstrate its deployment under nearly operational conditions. At the time of this writing, those efforts were in progress.

A final constraint was the project's budget. At the time of this writing, the team was preparing to submit its proposed testing budget to Draper Labs. Depending upon Draper's response to this proposal, the budget could become more or less of a constraint to the test plan as it currently stands.

7.4 Tools and Deliverables

7.4.1 Identifying the Tools

The first step in developing the test plan for the project was to determine what tools would be available to the team. Once the tools were identified, how the tools could be used to achieve the project's goals could be decided. The tools identified by the design team could be broken down into three categories: tools for high-g testing, tools for aero-propulsive performance testing, and tools for hardware and software development .

High-g Testing Tools

Four tools were identified for high-g testing. The first is the centrifuge facility at Draper Laboratory. These centrifuges have some advantages and some disadvantages. Their primary advantage is ease of access. Since they are located in Draper Labs, they will be relatively easy for the team to use. The centrifuges do have, however, two drawbacks: their size and how they apply loads to test items. Draper has two centrifuges, one with a test section that can hold items up to 1.60 inches by 1.60 inches by 2.05 inches in size and a new centrifuge, scheduled to be completed in June, 1997, which will hold items up to 1.99 inches by 2.00 inches in diameter. These size constraints limit what can be tested in the centrifuges. The centrifuges' second drawback is how g-loads are applied. In a gun, an impulse is applied in a very short time. In a centrifuge, g-loads slowly build. A centrifuge is not, therefore, a very good simulation of the actual gun launch load environment. What the team has learned, however, is that a centrifuge can provide an important first check: if an item can survive inside a centrifuge, it will have some chance of surviving a gun launch[18].

The next option for high-g testing being considered by the team is Picatinny Arsenal, which has three air guns: a two inch gun, a five inch gun, and a 155mm gun[19]. All of the guns function in the same basic manner. A test object is placed inside of a test cylinder, which is then sealed. At the back of the cylinder is a metal ring which presses against the end of the barrel as air is pumped in behind the cylinder. The ring is designed to fail at a specified pressure. Once this pressure is reached, the ring shears, and the cylinder is propelled down the gun's barrel. Air pressure is then used to slow the projectile down again as it travels through the barrel.

Though a better representation of an actual gun launch than the centrifuges, the air guns also do not provide exactly the same type of impulse loading. In fact, the impulse inside an air gun is actually shorter than an impulse inside a real gun. The design team has also been informed that the air guns can be used to exert higher forces than would be experienced in a real gun, and, if an item survives these forces, it will almost certainly survive a real firing[20].

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[18]Lecture by Frank Petkunas, Draper Engineer, for the MIT/Draper Technology Development Partnership Project, April 2, 1997.

[19] Data on the air and rail guns were provided to the team by John Grant, the operator of the systems, during a visit to the arsenal on February 25, 1997. Supplemental information was also provided by Frank Petkunas.

[20] Statement made by Frank Petkunas during an interview conducted by the author, April 8, 1997.

Another testing tool available at Picatinny Arsenal is their rail gun. This unit is an old 155mm howitzer now fixed into the ground. A set of rails has been attached to the end of the barrel. When a projectile is fired, these rails guide the projectile into a large pool of water, which is used to slow the round. The major advantage offered by the rail gun is that it is a real gun -- the loads that would be applied to a test object correspond to the exact loads that would be felt in a real firing of 155mm howitzer. The only limit to this real environment is that the projectile would not be free to travel through the air, but would instead be constrained to travel down the guide rails.

The final tool being considered for use by the team is a real gun launch. As of the time of this writing, the team is investigating the feasibility of such an option.

Aero-propulsive Tools

The primary tool that will be used to demonstrate the aero-propulsive performance of the flyer will be an actual prototype of the vehicle. As will be discussed, the team intends to drop this vehicle from an aircraft to demonstrate that the aerodynamic configuration was in fact controllable and that it delivered the performance predicted by the team.

In addition to the flying prototype, the team also intends to use computer simulation to help design and then validate the aerodynamics of the flyer. Computer simulation would also play an important role in demonstrating the interface between the aerodynamics of the vehicle and its flight control systems.

The final tool to be used in aero-propulsive testing is a series of table top tests. Still under development at the time of this writing, the purpose of these tests would be to demonstrate the performance and functionality of the engine for the flyer.

Hardware and Software Development and Testing Tools

The primary tool intended to help develop the hardware and software for WASP's systems is computer simulation. The simulations will be used at a variety of levels, building up system functionality in incremental steps. These simulations will help to first design the hardware and software systems for the flyer, and then also serve as a means to validate the functionality of those systems.

In addition to the computer simulation, the team decided that many of the software systems will be used in table top tests with other components. For example, once the flyer's flight control system is operational, it will be connected to the actuators that will be used in the flyer. The software will then be allowed to control the actuators, verifying that the program operated as intended. Similar tests were designed for the other software-dependent subsystems.

7.4.2 Defining the Ultimate Deliverables

To answer the question, "what should be tested?" the team found it easier to first address a different question: "what should the ultimate deliverable be?" The answer developed by the team was shaped by the project's constraints. The most significant of these constraints was component availability. The team knew from the beginning of the test plan development that g-hardened electronics would most likely not be available. The lack of such components meant that a flyer which could demonstrate the complete functionality of an operational vehicle, including the gun launch, could not be developed.

To overcome this limitation, the team proposed that two final products be developed: an air drop test vehicle (ADTV) and a high-g test vehicle (HGTV). The ADTV would be designed primarily to validate the aerodynamic performance of the flyer. It would be tested by being air-dropped from an aircraft. The secondary goals of the ADTV were to demonstrate as much of the functionality of the operational system as possible (in terms of autonomous operation and image taking) and to demonstrate the deployment sequence. To accomplish the autonomy-related goals, non-g-hardened components could be used, reducing the price of such equipment to the point that it was feasible for the team to consider their purchase. To demonstrate the deployment scheme, the ADTV would be dropped from its carrier aircraft in its stowed configuration, but most likely with its parachute already deployed. The ADTV would then complete the deployment sequence and fly its mission.

The HGTV would be used, as the name implied, for high-g testing. The vehicle would not incorporate any of the electronics of the operational vehicle. In place of these components, simulated equipment would used, basically weights with the proper shape and density of the real items. The HGTV would then be fired in Picatinny's rail gun to demonstrate that the structure of the vehicle would survive the gun launch. In addition to verifying the survivability of the structure, HGTV would also incorporate all of the moving components of the deployment systems. Though these systems could be activated during a rail gun launch, the team intends to confirm their functionality after the rail gun tests to prove the mechanical systems could survive the launch environment.

The detailed requirements for both the ADTV and the HGTV that were derived by the team are presented in Appendix G.

7.5 Subsystem Testing and the Integrated Test Plan

With the final goal now defined, the team stepped backward through the development process, asking what objectives would have to be met before the ADTV and HGTV were assembled. The result of this process, the Integrated Master Test Plan (IMTP) is shown in Figure 7.2.

As shown in the figure, the test plan was divided into two major components: airframe and aero-propulsive systems, and hardware/software systems. The following sections describe the details of this plan.

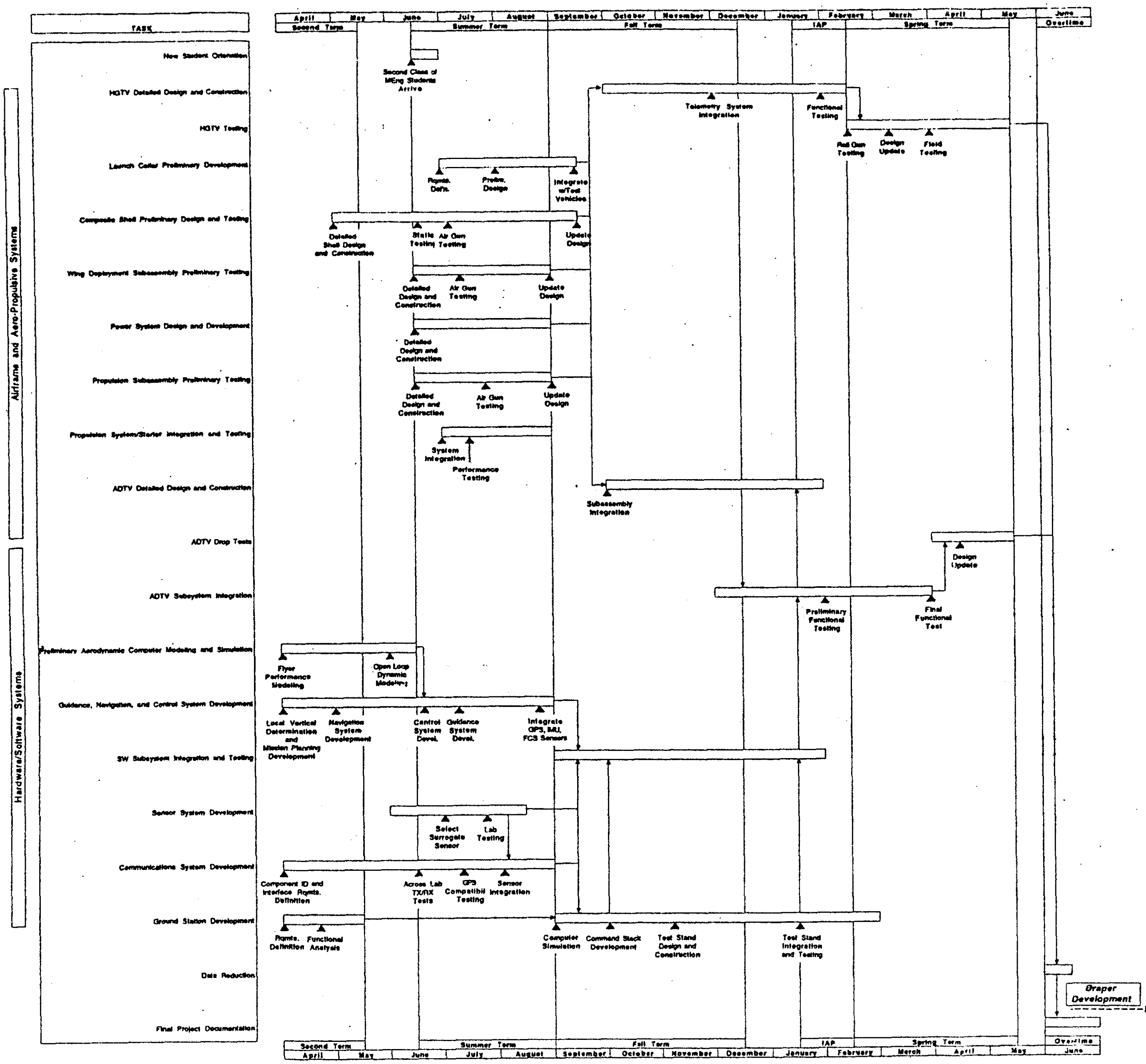

Figure 7.2 The Integrated Master Test Plan

7.5.1 Plan Overview

As discussed above, the team took great pains to ensure that the test plan followed a logical sequence which built-up subsystems into integrated systems. This integration flow can be seen clearly in the IMTP. The process will begin with detailed design of the flyer. This design process then feeds into each of the major subsystems: the launch collar; shell design/flyer structure; wing subassembly; propulsion and power systems; navigation, flight and mission control systems; communications; sensors, and ground station. Each subsystem then progresses through its own series of milestones (see below). On the airframe side, the first major integration task is scheduled to occur once the composite shell, wing systems, and propulsion systems had passed their high-g tests. This initial integration is to lay the foundations for the final construction and testing of both the ADTV and the HGTV.

Meanwhile, the software subsystems will be progressing along similar lines. First, each subsystem is to be demonstrated in a stand-alone mode through computer simulations. As each subsystem's functionality is verified, it will be integrated with another system. These steps are intended to reach a major milestone at the beginning of the project's second academic year, when all of the software systems are operated together in large-scale simulation.

While this large-scale simulation was being conducted, the test plan calls for construction to begin on both flyer prototypes. At that point, the HGTV will progress along its own path, culminating in high-g rail gun tests. Simultaneously, the ADTV airframe will be integrated with the software subsystems, once those systems have been verified through simulation. The integrated ADTV will then undergo a final test series.

The last steps in the IMTP are data reduction and the preparation of the final report. Assessing the lessons learned from the tests will be the essential concluding step of the project. Data discussed in the final document will be a critical element of any attempt to develop the WASP concept into an operational system.

7.5.2 Launch Collar Development

At the time of this writing, the details of the launch collar had not yet been worked out. In terms of testing, the IMTP indicates that launch collar development will begin at the end of June with requirements definition. Once these requirements are developed, launch collar detailed design will begin. At that point in time, the team will likely develop a more refined test plan for this design element.

7.5.3 Composite Shell/Flyer Structure Development and Testing

The team chose to pursue the composite shell because of the advantages it would offer in terms of reduced weight and increased internal volume. As the test program was being planned, it was discovered that the team was entering a relatively unexplored area of composite materials. Although the use of composites is becoming more and more common, few these applications have exposed the materials to the types of loads encountered during a gun launch. Despite the relatively unexplored nature of this realm of composites, the team was encouraged to pursue the design: by moving composites into a new environment, the team was fulfilling the requirement to include an element of "unobtainium" in the design.

Because of the lack of design guidelines for using composites in high-g applications, a comprehensive test plan was developed. The composite shell design will first be tested staticly in an Instron machine. Once these tests have confirmed the basic structural integrity of the design, several simple composite cylinders will be tested in Picatinny's air gun. The first of these tests will be completed using simple hollow cylinders. Once the tests have confirmed that the cylinders can support their own weight under the applied loads, an "endmass" will be added to the front of the cylinder. This mass will simulate the combined masses of the components that will eventually be installed in the WASP flyer. Once these tests are successfully completed, slots and holes would be added to the cylinder, simulating the effects of the cuts that will be made through the fuselage of the real vehicle. The largest of these cuts will be the slots through which the wings will deploy. So long as the cylinder passes these tests, the design will be integrated with the other airframe elements, and the HGTV will be constructed.

7.5.4 Wing Subassembly Development

The wing subassembly -- defined as the wings themselves, plus their deployment mechanism and structural supports -- represents one of the most mechanically complex portions of the design. Like the shell itself, the wing system test plan calls for tests using Picatinny's air gun. For these tests, the wing subassemblies will be placed in their entirety in a test cylinder for an air gun. The cylinder will then be fired, and subassembly inspected. In addition to simply surviving the test, the subassembly will have to be able to still function, i.e., the wing will still need to pivot on its mount, and the telescoping portions of the wings will still have to be able to slide. If these mechanisms no longer function, the design will have to be revised.

Assuming that the subassemblies do survive and retain their functionality, the data gathered from the tests will be incorporated into the design and construction of the two flyer prototypes.

7.5.5 Power System Development

Since the power system would not be required to be g-hardened (it would only be used in the ADTV), its development schedule is staggered compared to the other subsystems. Scheduled to begin during the summer of 1997, the power system development will begin with the detailed design of the power distribution system for the ADTV. This design will then be incorporated into the ADTV itself for operational testing.

7.5.6 Propulsion System Testing

The single most mechanically complex component designed into WASP was the engine. It was, therefore, considered to be one of the high-risk elements of the design. Two aspects of the engine in particular were of significant concern for the test plan: the remote starting system and the engine's high-g survivability.

As described previously, the engine which will be incorporated into the WASP design is a commercially available radio control model airplane engine. These engines are normally started by hand. In the case of WASP, this method of operation would obviously be unfeasible. A remote starter system was, therefore, required. The starter system, however, was intended for use with engines larger than the one being used for WASP. The integration of this starter thus increased risk element of the propulsion system. To reduce this risk, a separate testing path was established to allow for table top integration of the starter system with the engine. With the engine fixed to a test stand, the starter unit will be installed, and then the performance of the engine checked. Once the systems are functioning properly, they will be cleared for integration with the ADTV.

In parallel to this effort, the propulsion system will also be undergoing a series of high-g tests. Due to its mechanical complexity, the first high-g tests planned for the engine are in Draper's larger centrifuge. These tests will be used as a first check of the engine's survivability. If the engine does survive the centrifuge, the next set of tests will be conducted in Picatinny's air gun. Like the wing subassembly tests, the engine will be integrated with its support structure and deployment mechanism for the tests.

In the event that the engine failed any of its high-g tests, the result will not impact the rest of the test plan too severely. The main application for the engine in the test plan is in the ADTV, which will not be exposed to the high-g environment. If the engine were to survive the high-g tests, it is planned that the engine be integrated with the HGTV. If the engine fails to qualify for high-g's, however, placeholder weights will be used in the HGTV.

The ramifications of the engine failing under the high-g loads would be somewhat more severe for the WASP concept as a whole, however. Such a failure would imply that a separate development program would be needed to develop a g-hardened engine. While such a goal is not impossible (g-hardened actuators already exist), it would represent another challenge that would have to be overcome prior to the development of an operational WASP system.

7.5.7 Autonomous System Development

The autonomous systems of WASP incorporated several separate subsystems: the flight control system, the guidance system, the navigation system, and the mission planning system. To develop all of these components in the time allotted for the project required several parallel efforts.

One of the first of these efforts to begin is the development of a method for the flyer to determine the local vertical, i.e., "which way is down?" Making such a determination has been difficult for autonomous systems but is also critical for WASP to function properly. Given that the vehicle will have to aim its sensors to a point on the ground, it is important that the vehicle know where the ground is.

In addition to addressing this problem, the software group, in conjunction with the Program Integration Team, began finalizing the mission sequence, both for the operational vehicle and the ADTV. Once the mission is clearly defined, the functions that will have to be executed by the vehicle can be determined, and, from the sequence of functions, a mission planning system can be developed. The design of that planning system is then the next step in the process, as shown in the IMTP.

In parallel to the first two efforts, the software group is also working in conjunction with the aerodynamics group to develop the final aerodynamic configuration of the vehicle. Once this configuration is set, the software group will implement an open-loop flight simulation of the design. The control algorithms for the flight control software will then be based on the results of this open-loop simulation.

Slightly staggered in the development effort, the navigation system development will begin just at the close of the 1997 spring semester. This development effort is coupled to that of the mission planning effort, but significantly so. Not considered a critical path in the software development, once it is developed, it will be shut down and taken up again for systems integration.

Once the control laws for the flight control system are written, the first level of software integration will take place. Combining the mission planning software with the control system software will yield the guidance section of the control code. Once this integrated system is debugged, it will be integrated with both the navigation software and the local vertical determination software. The result will be a complete guidance, navigation, and control -- GNC --

software system. To verify the system's operation, the software will then be integrated with flight control sensors, global positioning system (GPS) equipment, and inertial measurement units. At the time of this writing, it was not yet clear whether these additional components would be actual hardware to which the software was connected or simply simulated items.

After this integration is completed, the system will be incorporated into a flyer computer simulation to demonstrate and verify the complete functionality of the GNC system. The next step in the process will be to integrate the GNC system with the other software systems.

7.5.8 Sensor Development

Since the team had made the decision to not incorporate high-g electronics into the ADTV, the high risk nature of the sensor was greatly reduced. The team would simply incorporate an existing micro-camera, such as those that can be purchased from *Edmund Scientific*, for instance. Due to the simplified nature of this task (as compared to integrating a system such as the *Xybion* camera), the sensor development is staggered relative to other aspects of the development effort.

Once the sensor is acquired, it will be integrated with the communications systems, to verify that the communication system can transmit the images effectively. The sensor will then be integrated with the GNC system along with the communications system.

7.5.9 Communications System Development

The communications architecture finally chosen for WASP represented a novel use of the GPS receiver. Due to this uniqueness, the risk associated with the system increased. To reduce this risk, therefore, a sequence of tests are planned to validate the overall operation of the communications system prior to its installation on the flyer. The first step in this process is to identify the components necessary for testing. Once these have been acquired, the system will be configured to send and receive signals across an indoor laboratory. The system will then be integrated with the GPS system and tests conducted to ensure that the systems do not interfere with one another. At that point, the IMTP calls for the system to be integrated with the other software systems for eventual installation in the ADTV. At the time of this writing, however, it was not clear whether that integration would be possible. If it is not, a surrogate communications system will need to be installed into the ADTV[21].

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[21] Matthew Burba, *Systems Design and Communication Subsystem of an Innovative Projectile*, Cambridge: MIT Press, 1997.

7.5.10 Ground Station Development

The last element of the WASP system that will be included in the demonstration program is the ground station. Initial definition of the requirements will be completed at the end of the 1997 spring semester. Due to the fact that the student working on the ground station will be away from MIT for the summer, the system's development will be put hold during that time. Its development will resume in the fall of 1997, following two paths.

The first of these paths is the development of a command stack. This stack is a series of commands that the ground station might transmit to the flyer. To simplify the development of the ADTV, however, two-way communications between the flyer and the ground station will not be attempted. Instead, the command stack will be downloaded into the flyer prior to a test. The ADTV will then execute the commands in sequence, as though they had been transmitted to the vehicle.

The second path in the ground station development will be the construction of a test stand. This stand will serve two purposes. First, it will operate as a test environment for the design of the user's displays and interfaces. Second, it will serve as a telemetry display for the data sent back from the ADTV during its test flights.

7.5.11 HGTV Development

Design of the HGTV is planned to begin with the start of the 1997 fall semester. The intent is to have the vehicle ready for its test series shortly after the change of the year. During construction, some telemetry equipment will be incorporated into the HGTV, to be used to measure the forces experienced by the vehicle.

The first set of tests planned for the HGTV are scheduled to take place in Picatinny's rail gun. For these tests, the entire HGTV will be placed inside a custom-designed test cylinder. The cylinder will then be fired by the rail gun, exposing the HGTV to the g-loads it will experience during a real launch. The vehicle will then be removed from the cylinder and thoroughly inspected for damage. The deployment system will be checked, to confirm that it still functions. The IMTP allows for a series of tests to be conducted in the rail gun, complemented with any redesign that may be required. Given the short amount of time remaining in the project at this point, however, it will be unlikely that any major design changes can be implemented.

The IMTP then calls for field testing of the HGTV. At the time of this writing, the design team was still investigating the feasibility of such tests. In the event that field testing proves to be impossible, the team will have gathered a very large portion of the data that such tests would have yielded through the rail gun tests anyway. The additional data provided by the field tests would primarily relate to the vehicle's flight performance during its ballistic cruise and the transformation from projectile to flyer. Though these are not trivial aspects of the design, the rapid pace of the project may require that some sacrifices are made. If the field tests can not be completed, the team will still have gone a long to proving the viability of the WASP concept.

7.5.12 Development of the ADTV

The development of the ADTV is first and foremost dependent on the design of the major subassemblies of the vehicle: the wing subassembly and the propulsion system. Although these systems do not need to survive high-g testing to begin development of the ADTV, the intent of the IMTP is that the ADTV be high-g capable except for the electronics. This goal was established to help ensure that the ADTV is as accurate a prototype for the operational system as possible in terms of its aerodynamic performance. To some degree, this performance will be affected by how the vehicle was constructed . For instance, if the vehicle's structure requires strengthening to survive the launch, this modification will add weight to the vehicle, changing its aerodynamic performance.

The IMTP also calls for the integration of the software elements of the WASP design with the ADTV. The feeling of the team at the time the plan was developed was that the ADTV should attempt to demonstrate as much of the functionality of the flyer as possible, in terms of autonomy and sensors. In the event that there are problems with these systems, however, the ADTV can be designed to operate with a reduced level of functionality, perhaps being remotely piloted instead of autonomously controlled, for instance.

Presuming that there are no major hurdles which prevent the software systems from being incorporated into the flyer, the integration is scheduled to take place beginning in December of 1997 and continue through March of 1998. In parallel with the integration effort, systems will be tested on the ADTV while the vehicle is mounted in a test stand on the ground. This will allow the team to verify the operation of all of the system elements prior to releasing the vehicle in the air.

Once all of the subsystems have been integrated and their operation verified, the ADTV will start air drop testing. At the time of this writing, the detailed arrangements for the air drop test program are in the process of being developed.

7.6 Projected Project Status at the End of the Demonstration Program

At the end of the test program, the team hopes to have demonstrated two separate but related aspects of the WASP concept. The high-g subassembly testing along with the HGTV tests should have validated the high-g survivability of the WASP design. In addition, the subsystem development and simulation, in conjunction with the ADTV, should have validated the functionality of the vehicle. Therefore, although the entire system would not have been subjected to the complete mission scenario, all of the major elements of the design will have been proven in their most important points in the mission. The structural design will have been validated in the HGTV and the systems will have been validated in simulation and the ADTV.

At that point, the next step in the development of WASP would be to replace any non-g-hardened components with ones which were g-hardened. A new series of air drop tests would then be warranted to confirm the systems operation. These tests could then be followed by high-g tests and then field tests of the system.

8. Project Status, Lessons Learned, Recommendations, and Conclusions

8.1 Project Status at the End of the First Year

As the first year of the MIT/Technology Development Partnership Project drew to a close, the team was continuing to develop the flyer's configuration and beginning to move forward with the test plan. Following is a description of the status of each specialty group at the middle of May, 1997.

8.1.1 Program Integration Team

Two of the three members of the PIT were leaving the project with the end of the academic year. The author, however, was staying on the project through August, 1997. At the end of the 1997 spring semester, the PIT was moving from coordinating the conceptual development of the WASP system to focusing its energies on coordinating the integration of all of the subsystems into the forthcoming flyer prototypes. To that end, the PIT was conducting functional flow analyses of the vehicles, helping the subsystems to develop and then coordinate their test plans, and integrating subsystem schematic block diagrams into a complete system design structure matrix. This last activity would lead directly to detailed design component placement in the flyer.

8.1.2 Flyer Aerodynamics Group

The graduate student responsible for this aspect of the WASP design finished his Master of Engineering degree while continuing the development of the aerodynamic configuration of the vehicle. As this effort is completed, the detailed design of the rest of the flyer will begin, though this process will not start in earnest until the mid-June, 1997. At that time, the team plans to re-analyze the aerodynamic configuration to determine if the flyer's performance can be improved.

8.1.3 Flyer Propulsion Group

At the close of the 1997 spring semester, the propulsion group was about to begin its test program. The student who had been working on this system during the academic year was remaining until August, 1997, to continue his work. This continuation meant that development of the propulsion system could progress without interruption. At the time of this writing, the engine and its associated equipment are being ordered. Performance testing should begin by June.

8.1.4 Communications Group

The communications group finalized its system architecture at the close of the spring semester. Prior to graduating, the Master of Engineering student working on the system was attempting to identify the components that would be used in the test vehicles and finalizing the testing plans for the system. Responsibility for this system will be passed onto a new team member during the summer term.

8.1.5 Navigation, Flight, and Mission Control Group

Run by a Master of Science degree candidate, this group was continuing its software development without interruption. Significant progress had been made in the local vertical determination effort, and aerodynamic simulations of the flyer were being developed.

8.1.6 Ground Station Group

As previously noted, the Master of Science student pursuing this aspect of the design was leaving MIT for the summer. He had defined the needed functionality of the ground station in terms of its role in the upcoming test program. These functional definitions would lead to a formal set of requirements for the ground station, to be written in September, 1997.

8.1.7 Sensor System Group

Since the team made the decision to use a surrogate sensor in the ADTV, the sensor group had been fairly dormant toward the end of the semester. It was expected that a new student would take over work in this area during the summer to select and then integrate the sensor which would be used for the ADTV.

8.1.8 Shell Design and Integration Group

During May, 1997, a new undergraduate research assistant was hired by the design team. Throughout the month, he took over most of the responsibilities related to this design group. At the time of this writing, the student was in the process of estimating costs and lead times for items related to the first set of composite shell tests to be carried out in the air gun at Picatinny Arsenal. These tests should begin sometime late in June.

8.2 Recommendations for further Work

As the semester draws to a close, one component seems to present the greatest risk to the project: the propulsion system. The high mechanical complexity of the engine could lead to early failures in the test program. While these failures would not doom the test program (the ADTV would be unaffected by problems related to the high-g environment), they would represent another obstacle that would have to be overcome prior to the development of an operational system.

The reason for concern regarding this issue, however, relates to the potential for WASP to compete with the Army's initial design, which is a glider. The reason the design team chose to pursue a powered flyer configuration was that such a design seemed to offer significant performance advantages over a glider without a significant increase in cost. If a development program were required for the engine, however, this analysis would change. The cost of the propulsion would almost definitely increase. As part of the g-hardening process, the engine's structure would likely have to be reinforced. Such reinforcement would increase the engine's weight, while decreasing its performance. These changes could significantly reduce the advantages offered by the propulsion system.

From a risk management point of view, the design team should make every effort to investigate other propulsion system options as well as consider the removal of the engine all together. One of the reasons for selection Supershell over the glider variant was that Supershell allowed for the engine to be removed while the glider did not allow one to be added. This design flexibility was a major driver behind the decision to pursue the Supershell concept, and it should not be forgotten as the test program develops. If problems are found with the propulsion's system ability to survive the high-g environment, the team must be ready with a viable alternative, whether it be a different propulsion system or none at all.

Changes in the shell's firing and ballistic characteristics due to the use of composite materials also need to be further researched. The composites were used in the design to reduce the flyer's weight while it is loitering on station. The consequences of this weight reduction on the vehicle's performance while in the shell configuration, however, are not yet clear. Any weight reduction (compared to a standard shell) will result in an increase in the forces felt by the vehicle at launch, possibly requiring a more robust structure than originally predicted. In addition, the weight change may also affect the shell's flight characteristics during its ballistic cruise. These effects must be more completely understood in order to finalize the vehicle's design.

From a more general perspective, the author is also concerned about potential problems arising when the final attempt is made to install the necessary components in the ADTV. During the development of the requirements for the ADTV and the HGTV, the idea that the ADTV be a scaled vehicle was suggested. Rather than building a small-scale prototype, as is usually done in aerodynamic testing, it was proposed that the ADTV be scaled *larger* than the operational vehicle. By increasing the vehicle's scale, more volume would be available, simplifying component installation and integration. The design team was cautioned by members of Draper Laboratory to avoid such an option[22]. These engineers suggested that the majority of the functionality of the vehicle's subsystems could be effectively demonstrated in simulations conducted on the ground. The purpose of the ADTV would be to validate the vehicle's aerodynamics. Any additional functionality incorporated into the vehicle would be counted as a bonus, but the vehicle's size should not be changed for the sake of incorporating such functionality. The author hopes that the continuing and future members of the design team will abide by the advice given by the Draper engineers. Altering the ADTV design too significantly might invalidate its aerodynamic performance compared to the operational vehicle's, negating any benefits of having conducted the tests in the first place.

For these reasons, the team must approach the systems integration task with caution. Problems will undoubtedly arise during the integration process. Prior to entering into this process, the team must reassess its risks in a more formal manner than was conducted prior to developing the integrated master test plan. A formal risk assessment will help to highlight expected trouble areas, so that potential solutions and alternatives can be developed prior to the problem being encountered. Such an assessment would be very valuable when attempting to trade functionality and space, should this become a problem in the ADTV. Since the ADTV's purpose is to validate aerodynamic performance, the team might consider omitting functions that are considered high risk. These elements might be better tested on the ground than in the flyer to reduce the risk associated with the functions.

Finally, it will be important for the design to team to remain flexible. The schedule laid out in the IMTP is extremely tight -- a slip at one point in the schedule could have severe consequences for the entire project. To avoid these consequences will require that the team have a clear

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[22] Comments to this effect were made by Brent Appleby and David Kang, both Draper engineers, during the team's Conceptual Design Review, presented on April 16, 1997.

understanding of the risks associated with each element of the design and that plans are made in advance to deal with problems that arise. Though the test schedule is tight, time lost at one point could be made up at another point. If, for instance, problems develop in the design of the communications system, its integration with other software elements can be delayed until later in the development effort, perhaps directly integrating the system into the ADTV rather than with the other software systems first. The key to coping with the problems that arise will be to anticipate as many of them as possible, and to retain enough flexibility and creativity to address those that were unanticipated.

8.3 The Operational Future of the WASP Concept

8.3.1 Competing for Military Missions and Dollars

One of the reasons that this project was originally chosen by Draper Labs was the apparent interest in the concept shown by both the United States Navy and Army. Interest alone, however, does not guarantee a contract. If the MIT/Draper design team accomplishes its development program successfully, Draper will still be faced with the challenge of obtaining a procurement contract from the military. Budgets are slim at the present time, and it may prove difficult for funds to be found to acquire a WASP-type system.

In addition to budget constraints, the WASP concept will also be embroiled in a hotly contested marketplace. The military is quite interested in UAVs at the moment, an interest expressed in several procurement programs currently underway and several more waiting in the wings. The competition in many of these programs has been intense, with several companies offering bids for many of the contracts. A WASP-type system will first have to compete with many other reconnaissance systems to prove that it offers advantages over other vehicles. If it survives this competition, Draper will then likely have to beat several other proposals to win a production contract.

The author believes that the key to winning such a contract will be to have a thorough understanding of the limits of competitors' systems and the limits of the WASP system as well. As described earlier in this work, the design team eventually decided that the mission niche best suited to WASP was for high-value, time-critical targets at the company level or below. To be procured for this mission, the unit cost of WASP will have to be kept to a minimum, as will the training required for its use. Achieving these goals will likely mean that some performance will have to be sacrificed. The author believes that such sacrifices should initially be made. Once the system has entered procurement, pre-planned product improvements should then be offered to incrementally increase the system's performance without substantial increases in system cost.

Finally, in keeping with the concepts just described, the temptation to enable WASP to compete with other reconnaissance systems, such as larger UAVs, should be avoided. WASP does face significant operational challenges. These challenges should be accepted and understood, and the design's performance matched to these limits. While it might be technically possible to enable WASP to stay aloft for eight hours, it is not clear from the analyses conducted by the team that such a capability would really improve the system. Most likely such capabilities would dramatically increase the system's cost, while at the same time still delivering less performance than what is offered by the larger UAVs. In summary, engineers who might continue to develop the WASP concept should abide by a tried and true engineering slogan: "keep it simple!"

8.3.2 Finding Civilian Applications

One of the initial requirements for the MIT/Draper Technology Development Partnership was that whatever system was pursued by the design team have some civilian application. While the original requirements document did mention that WASP be adaptable to civilian applications, the design team did not thoroughly explore those options.

Some civilian applications do seem feasible, however. In the event of large natural disasters, such as forest fires or floods, a WASP system could be deployed with the National Guard. The system would provide a quick, cheap reconnaissance tool to look for survivors of the disaster or to assess damage. WASP's disposable nature would also be well-suited to disasters such as nuclear reactor meltdowns, like the one which occurred in Chernobyl, Russia. Non-military applications do, therefore, exist for WASP, and engineers who work on the design in the future should pursue these applications. If civil officials can be convinced of the utility of a WASP-type system, more systems would be procured, potentially lowering the unit price.

8.4 Recommendations for Future Joint Endeavors

Without doubt, the experiences of the design team working on this development project were extremely rewarding. As students, many of us learned a great deal about specific technology-related issues, and we all learned a significant amount about engineering entrepreneurship and project management.

The author does, however, have several recommendations to make the experience even more rewarding for students involved in similar projects in the future. The first recommendation relates to the project selection process. When this design team first began to develop project concepts, the team was informed by Draper personnel that the design team would be responsible for selecting the final project. Ultimately, however, such was not the case, and the project chosen by the team was discarded by Draper in favor of what has since become WASP. This unexpected change was somewhat of a blow to the design team's moral.

The author recommends, therefore, one of two possible modifications to the process for future projects. One option would be to genuinely allow the design team itself to choose the final project. Putting this much power in the hands of the design team may not be the best solution, however. It is possible that the students on the team could all be interested in pursuing a project that does not match with Draper's capabilities.

A better solution to this problem would be for Draper personnel to provide more refined preferences for project focus areas than was the case during this first attempt. Rather than having the design team pursue projects in several potential focus areas (as this design team did), the team's resources might be better utilized if a the focus areas themselves were first narrowed. Using the areas generated by this design team as an example, once the team had decided that innovative projectile systems, intelligent cooperative systems, inexpensive launch capability, and advanced aircraft navigation showed the most promise, Draper might have told the team to focus on one of these areas. The design team could then have investigated several possible specific market opportunities under this one general focus area.

Such an approach would have several advantages over the one followed by this design team. By ensuring that all of the potential projects are kept within one focus area, market information uncovered while pursuing one project might be useful by another project. This potential for overlap would allow the team to focus its energies much more than was possible during this first endeavor. In addition, this potential for overlap in initial research would prevent feelings among team members that work was wasted for a project that was not selected. As long as all of the projects are complementary, the marketing research done for all of them could be shared between the concepts, most likely leading to a more thorough development of the concepts than was achieved during the first part of this year's effort.

A second recommendation for the market assessment would be to move the process away from a technology push approach toward a user pull[23]. The method followed by this design team could be said to represent a technology push approach to the market assessment. The team developed five technology concepts -- the solar sail, the hybrid launch system, ASARS, and the reconnaissance projectile -- and then sought to understand whether or not such systems would be marketable. In essence, the team developed several candidate projects and then sought applications which would be marketable.

[23] Jacques S. Gansler, *Affording Defense*, Cambridge: The Mit Press, 1991, p. 144.

A better approach would be to follow the user pull. Such an approach would first seek to define a potential market and identify its customers. The team would then seek to develop a thorough understanding of those potential customers' needs. Once such an understanding was obtained, the team would then brainstorm technology solutions for those problems. The team's project would then emerge from these concept brainstorms.

This revised approach offers several advantages over that taken by this design team. First, the projects that are developed will have a clear market into which they could be sold. This team was able to find markets for its proposed projects, but the projects came before the markets, instead of the other way around. In addition, a user push approach would improve the project's competitive edge within a market since the team's project would directly address the needs of the customers. Another advantage to this alternative approach is its potential to inspire the design team. Future teams would develop a much greater understanding of the customers' needs than the first team did. This greater understanding would improve their problem solving process and possibly lead to more creative design solutions. Finally, this approach would teach engineering students a valuable entrepreneurial skill. Many companies in a variety of industries are now adopting customer-focused product development processes. Boeing, for instance, refers to "aggressive listening,"[24] and many other industries talk of understanding the needs of the user. Teaching students involved in these projects such approaches would be a valuable lesson for them to carry into industry.

The author's third recommendation would be for Draper and MIT to attempt to clarify their planned interactions earlier in future projects. At times, the relationship between Draper engineering personnel and the design team was unclear. Unfortunately, Draper personnel were often important first contacts for information needed by the team, particularly in a project so militarily-oriented as WASP. Draper staff and MIT faculty should, therefore, take the time to explicitly explain to the design team what the relationship between Draper engineers and the team will be as early as possible. Such a clarification will simply smooth the progress of the project.

The final recommendation for future projects relates to potential focus areas. As mentioned, the WASP concept was a system aimed primarily at the military market. While no one on the design team had any objection to working in this field, it did pose some problems for the team. First, since several of the students on the team were not US citizens, they were often excluded from visits to military facilities. In addition, even for those members of the team who were US citizens, it sometimes proved difficult to find certain information for security reasons.

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[24]Karl Sabbagh, *Twentry-First-Century Jet: The Making and Marketing of the Boeing 777*, New York: Scribner, 1996, and Paul Proctor, "New Strategic Focus Drives Boeing Transformation," Aviation Week and Space Technology, April 28, 1997.

Draper might wish to consider, therefore, future projects with a significantly more commercial "lean" to them. Working on projects destined for civilian applications would avoid any difficulties in having foreign students on the team and would also enable the team to avoid needing classified military information.

With or without these recommendations, the author believes future projects undertaken jointly by Draper Laboratory and MIT will be rewarding and successful experiences for all those involved. Implementing some of the above recommendations would simply improve an already extraordinary experience for future engineering students.

8.5 Management Lessons Learned

For all of us working on this project, the experience was a new one. Rough plans were initially laid out for the work to be done, but no one had a perfectly clear vision of exactly what that work would entail or what other work might be needed. As the project progressed, these plans were revised and refined. In these final sections, the author will present some of the lessons learned relating to the management of the project. The first several sections will review some detailed issues, while the final section will present a model system engineering management plan (SEMP) that could be used as a foundation for planning future projects.

8.5.1 How to Complete QFDs, FFDs, and Similar Tasks

One challenge faced by the design team was how to complete tasks such as the QFD matrices and the FFDs. The creation of these analysis tools posed a problem because these activities offered their greatest advantages when they included insights from the entire team. This fact was particularly true for the QFD matrix, since it relied heavily upon brainstorming and technical knowledge. As will be shown, learning how to balance the need to allow for everyone's input with the need to accomplish the task in a coherent and timely fashion proved challenging.

Consider first the team's experiences with the technical requirements matrix. Several members of the design team initially chose to take on the responsibility for generating this matrix. Working on their own, they first reviewed the requirements document and then derived a set of technical requirements for each customer requirement. They then presented copies of the matrix -- without weightings, scores, or conflicts noted on the matrix -- to each team member. On their own, each member of the team then filled in the matrix and returned it to those who had originally developed the matrix. They then attempted to integrate the results of everyone's inputs.

Though the approach seemed straight forward, several problems were encountered. The first problems were disagreements over the technical requirements included on the matrix. Based on their own backgrounds, each member of the team interpreted the requirements somewhat differently, leading to different conclusions about what technical requirements ought to be included in the matrix. Understanding and integrating these diverse opinions proved difficult for the team members responsible for the QFD matrix. The second problem encountered was that it proved difficult to get all of the members of the team to complete the matrices on their own. This difficulty lead to several delays in completing the matrix.

Given the problems the team was encountering, it was decided to try a new approach. For the second attempt, a team meeting was called. At this meeting, the team first discussed the original customer requirements. Based on this discussion, the team generated weightings for each requirement in consensus fashion: a team member would suggest a value and then it would be discussed until a consensus on the value was reached. Next, the team brainstormed several technical requirements for each customer requirement. Invariably, the team would generate a very large number of these requirements, so the team discussed the merits of them, and then kept only those judged to be the most constructive.

With the basic foundations of the matrix finally clarified, the team was then asked to fill in the specific scores and conflicts independently. The team agreed that it was important for all of the team's members' opinions to be reflected in the QFD matrix. To do this during a meeting, however, would have required far too much time. The team decided, therefore, to have individuals fill out the matrix in their own time, but with a firm due date established.

In the end, this second approach worked fairly well, and the author would recommend it be followed by anyone needing to complete a QFD matrix as part of a team. The team also experienced similar difficulty in developing the FFDs. In this case, however, the problems were caused in the opposite manner. In the team's first attempt to develop an FFD for WASP, each team member was told to develop a diagram on his/her own. A team meeting was then held, where the team tried to combine all of the FFDs by marking functions on sticky notes and attaching them to the wall. While this approach allowed for everyone's input, it did not result in a high quality FFD.

The team's second try was to appoint several team members to develop the FFD. They began by generating a first guess of the diagram. Next, they consulted with each specialty group on the team to clarify sequencing and to see if any functions needed to be added or removed. This approach worked much better than the first, yielding a higher quality FFD that better reflected the needs of each specialty group.

The interesting aspect to these two experiences -- developing the QFD matrix and the FFD -- was that they both required input from the team. For one, this input could be easily obtained during a group meeting. For the other, the input was best obtained from more direct dialogues with individuals. The apparent difference between the two activities was in the nature of required input. In the case of the QFD matrix, the required input was based on brainstorming, which is often highly effective in a group setting. Team members could simply shout out a technical requirement, since the ordering of these requirements was not important in generating other ones. The FFD, on the other hand, relied on brainstorming to some extent, but it also required a fairly structured, technical approach to the vehicle's functionality. One function might have influenced another, and their proper sequencing was essential. To generate the FFD required some analysis of how the various subsystems on the vehicle would operate, and such analysis could not be easily conducted in a large team meeting.

The apparent conclusion that can be drawn from these experiences, therefore, is that one must be cautious in deciding how to obtain input from a team. For a task in which team input can be received in a nearly random fashion, i.e., when unstructured brainstorming can be used, it is worthwhile to receive the input in a team setting. What one person says might inspire another, leading to better results than if each team member considered the question on his or her own. For tasks which require some structured output, however, such as a functional flow diagram, it is best for a small group to be made responsible to completing the overall task. This group should then seek input from other members of the team on an individual basis. The small group should then incorporate this feedback to generate the final product.

8.5.2 Team Meetings

During the course of this project, several lessons emerged regarding how to effectively run design team meetings. The first and most important was always have an agenda prepared in advance. If the team has some idea of what will be occurring at the meeting, they will be more likely to participate constructively.

Hand in hand with this first lesson, a second lesson was that any time the team needed to develop a plan of some sort -- whether it be for the approach to the design problem, how to deliver a presentation, or when to set due dates -- it was best to bring in a "first cut" to which the team could react. Asking for the team to develop a design schedule, for instance, never worked very well. If, however, the team was presented with a proposed schedule, they could react to it, and then make comments and offer suggestions for changes and improvements. These contributions could be enhanced even further if the "first cut" item could be given to the team prior to the meeting. They could then come to meeting with comments already prepared.

One problem that the team had early in the project was that design issues which needed to be addressed would be raised during a meeting. At the end of the meeting, however, these issues would be forgotten, because no one had been assigned to investigate the issues. As this problem was identified, steps were taken to ensure that any design issue that was raised during a meeting was assigned to a specific person for investigation. Once a work breakdown structure had been implemented, these assignments became easier to make -- problems could be framed in terms of a specialty area and then assigned to the appropriate specialty group, i.e., an action item-approach.

As important as it was to assign these tasks, it was also equally important that they remain on meeting agendas until the issue was resolved. Once a person was tagged to complete a task, it was often the case that he or she needed to be prompted at a meeting to issue a report on the status of the task. The lessons to be drawn from these two experiences, therefore, were, first, to ensure that any issue that came up during a meeting was assigned to a person to investigate it, and, second, that the issue be tracked until it was resolved.

Complementing that tracking, another important lesson from this project was the need to keep minutes of design team meetings. The minutes often provided the only documentation of decisions made by the team, and they also served as a means of tracking assigned tasks. The design team also found that the most benefit from the minutes was derived when they were kept by the same person at every meeting. Having one person responsible for the minutes helped to ensure that they were completed and also maintained a standard style and format for the minutes from meeting to meeting.

The final, and perhaps one of the most important meeting-related lessons learned from this project was that meetings operate best if they are used for status reports and to assign work, but not when used to complete work. At several points throughout the year, attempts were made to use regularly scheduled team meetings as team work sessions. A task would be assigned, and the team would try to complete it. Though some degree of completion was achieved at such meetings, they were often not as productive as team members had hoped they would be.

A method that produced much better results was for separate times to be established to accomplish group work. For instance, once the team had decided to pursue the three WASP concepts of the Supershell, the Twin Shells, and a glider, the team decided the analysis would be best completed if the entire team met to work on the concepts together. During a regularly scheduled team meeting, the team decided on a time to hold this group work session. By planning the work session in this manner, the team knew clearly that when they arrived they would be expected to accomplish certain tasks. By following this approach, regular team meetings could be used for team members to update one another on their work and to highlight problems which they were encountering. If someone needed help on an issue, he or she requested the help at the meeting, but a separate time was always established to address the problem specifically. This distinction between doing work at a meeting versus reporting on completed work at a meeting was an important lesson to have learned. Without doubt, meetings were far more productive and worthwhile when only used for reporting problems and not for trying to solve them.

8.5.3 Schedules

An important lesson relating to team resource management was the need to establish schedules and to show how tasks completed by one person fed into the tasks that would be completed by others on the team. When firm due dates were not established for tasks assigned to people, the tasks often took far longer than necessary to complete. Assigning a specific due date to every task assigned to a team member helped the team function more effectively.

The team's effectiveness was increased even further by the development of a scheduling tool that not only showed due dates for certain tasks, but which also showed how the completion of one task would help another task begin. An example of such a task flow schedule is shown in Figure 8.1. Each schedule showed the tasks that would need to be accomplished by the team over a two week period. Every task was illustrated as a bar, showing when the task was started and how much time was available in which it could be completed. Arrows then indicated how information from one task fed to another, helping team members understand how their work fit in with the work being completed by the rest of the team. These schedules improved the teams functionality, especially in terms of team communication, a great deal.

All of the two-week schedules developed for the team are included in Appendix H.

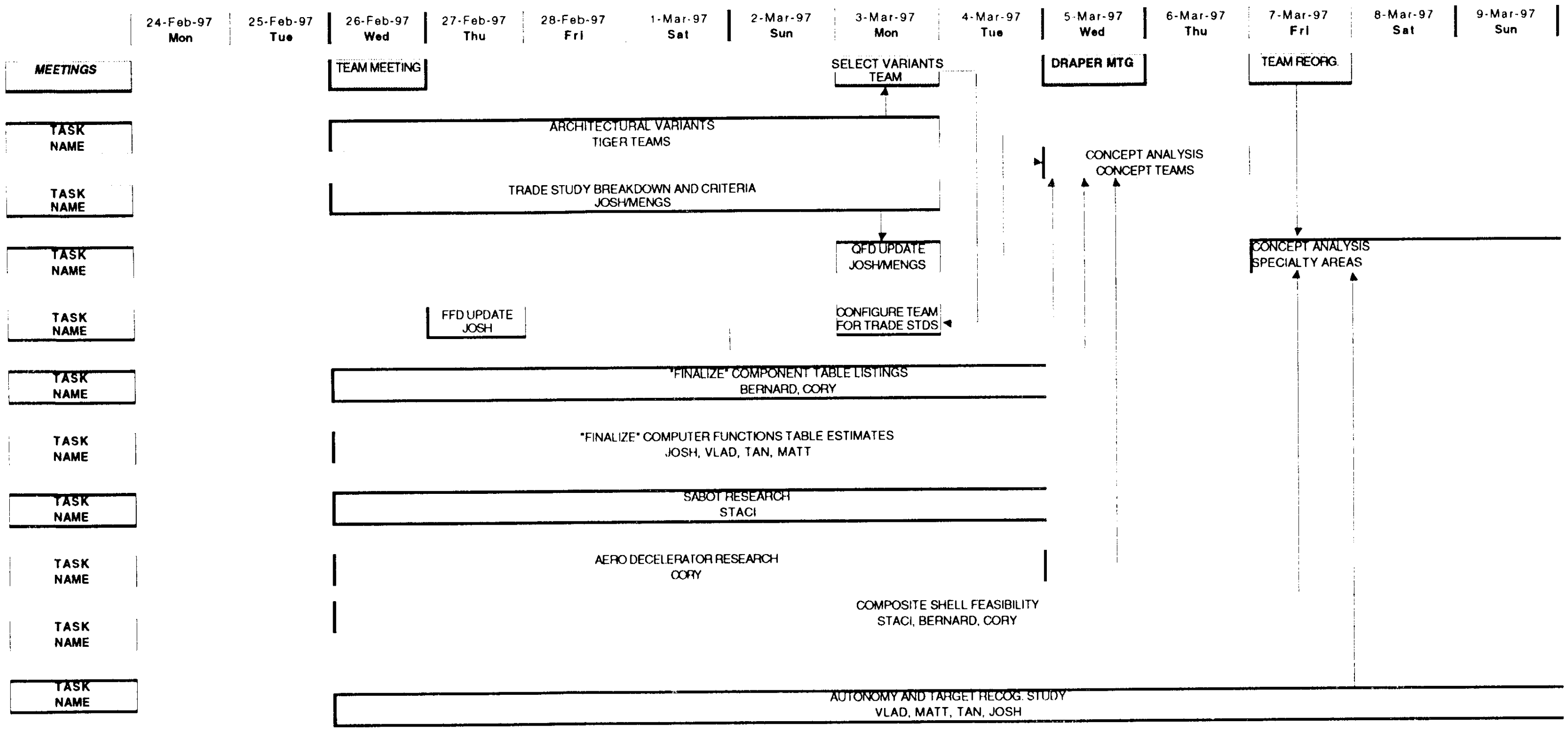

Figure 8.1 Sample Task Flow Schedule

8.5.4 Team Communication

This design team was large enough to experience several different types of communications problems. Some of these problems related to misunderstandings of who was doing what, while others related to data being recorded differently in different places, and still others related simply to some team members not informing other team members of what was going on.

The first type of communication problem -- misunderstandings of who was supposed to be doing what -- were effectively solved by ensuring that all design issues were assigned to a specific person. Making these assignments was simplified once a formal work breakdown structure had been established, as discussed above. Misunderstandings of who was responsible for what work were resolved easily in the project through these means.

Communications problems relating to data accuracy in various files was a problem which the team encountered late in the year, during the design analysis phase of the project. During this time period, many members of the team were working on all of the designs. Often data generated by one member had be to used by another member of the team. At these communication nodes, the data was, at times, "corrupted." The author believes that the best solution to this problem would have been a formalized method of data reporting. Since the design team was relatively small, team members would often simply ask another member verbally for a given piece of information. While this approach usually worked, there were a few instances in which it did not. These problems could have been avoided entirely had the team developed a formalized procedure for specialty teams to use to report design analysis results. The author strongly recommends that future design teams in the MIT/Draper Technology Development Partnership Project establish such methods.

The final communications problem encountered by the team paralleled the one just described: information dissemination. The best example of this problem was reporting of information gained during field trips. A team member would return from a trip and then relate what had been learned to other team members by word of mouth. Thus, while a few members of the team learned in detail what information had been gathered, other members of the team had no idea what had happened. This problem was redressed with the institution of a semi-formalized method of documenting trips using a set of bulleted notes that summarized what had been learned. Similar problems were encountered with information revealed at meetings, but these difficulties were subdued once a standardized method of recording minutes was established.

The conclusion from all of these problems, therefore, was that one must be aware of the need to formally document all major decisions made by the team, all significant data generated during analyses, and any information gathered from outside sources. Whether such documentation occurs via electronic mediums (such as e-mail) or with paper copies of reports, it is essential that all members of a team be kept informed of what occurs throughout the team. It also seems as though this documentation effort is enhanced if it is standardized, and, of course, if everyone on the team abides by that standardization.

8.6 A Systems Engineering Management Plan for Future Projects

When the author became responsible for managing this project, one of the first steps that had to be accomplished was the development of a systems engineering management plan (SEMP) for the project. Given that no one on the team had ever really had to complete such a task, it was not an easy thing to develop. Initial attempts were made, which served as useful guides for the team, but the team did not really appreciate what work would need to be completed until the project had actually under way.

Presumably each project pursued by future graduate design teams will be somewhat different. The essentials of every project, however, will remain the same: a project will have to be defined, its market viability assessed (and this assessment could and should impact the definition of the project), requirements will have be developed and reviewed, architectures and concepts developed, and, eventually, a product must be delivered. This common set of tasks form the backbone for a SEMP for these types of projects.

Using the experiences of this team, a model SEMP is illustrated in Figure 8.2 and Figure 8.3. The plan covers a two year project, presuming that initial research efforts, such as the national needs assessment and facilities and capabilities assessment, will need to updated over time. The plan then progresses through market assessment and initial project definition, into concept development, and then to prototype design, construction and testing. Each bar shown in the SEMP roughly corresponds to a section in this thesis. The interaction diagrams presented at the beginning of each section, therefore, can be used to help determine what specific activities should be completed during each major task bar on the SEMP.

The author stresses that since each project will be different, their SEMPs will also differ from the one shown here. The SEMP illustrated in the following figures, however, should serve as effective model to future project planners. The author hopes that its inclusion here will shine a bit of light into the dark tunnel one must peer down when initially attempting to plan such a project.

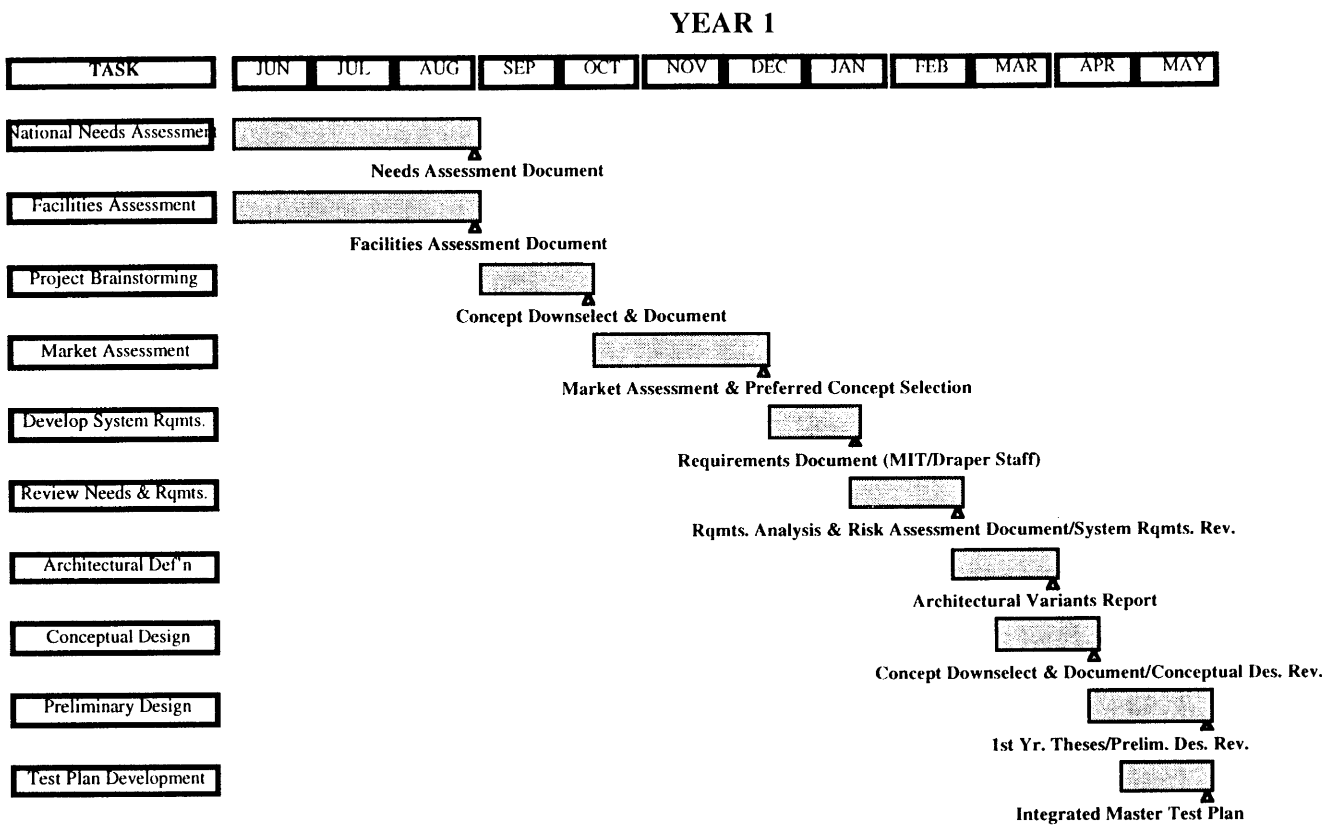

Figure 8.2 Recommended Year 1 Systems Engineering Management Plan

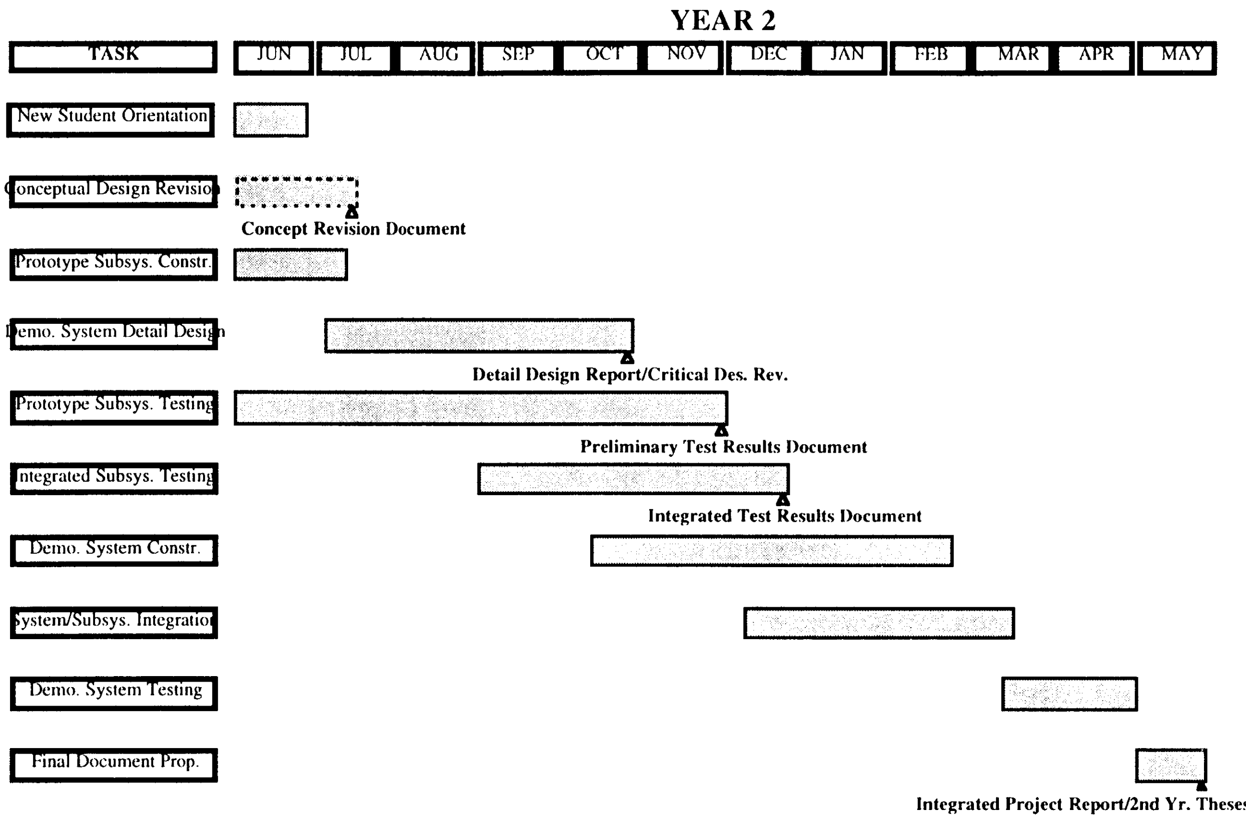

Figure 8.3 Recommended Year 2 Systems Engineering Management Plan

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Appendix A Solar Sail Demonstrator Marketing Document

Note: This section was written and researched with the help of David Iranzo-Greus.

Overall Description

Motivation

Space exploration has been enjoying increased popularity recently both for commercial and scientific reasons. A major obstacle in space utilization, however, is propulsion. Space power systems are often complex and expensive. While chemical rockets have proved to be reliable, there are missions where the fuel requirements for the rockets become prohibitive. Alternatives such as ion propulsion and nuclear rockets have been proposed, but each of these options face significant technological and political challenges. Other alternatives are needed.

Solar sail technology offers such an alternative. Initial spacecraft designs based on sails suggest that such a means of propulsion would be relatively inexpensive, and, for a variety of missions, offers advantages over other methods of travel (see references 1 and 2).

Background[3]

The idea of a solar sail is not an entirely new one. The theory of solar sailing has been around for quite some time, but an actual solar sail vehicle has *never been built and deployed.* This failure of theory to result in hardware can be traced to a variety of setbacks, some technical, many political. At the present time, however, there appears to be considerable interest in the technology at NASA, and the space agency has expressed some interest in potentially assisting with this project, were it pursued further by the design team.

Introductory Description

The solar sail demonstrator is intended to be a small, simple spacecraft to confirm the principles of solar sailing and to prove the enabling technologies that must be brought together to successfully operate a solar sailing vessel. It is proposed that the vehicle be boosted to geosynchronous orbit, where it would deploy its sail. The vessel would then control itself autonomously, spiraling away from the Earth under the propulsive force provided by photons from the sun striking the sail. If the mission were properly timed, this spiraling trajectory would allow for a mission to the moon (see below).

As shown in Figure A.1, the vehicle itself consists of three principal elements: the sail, the rigging, and the payload. Please note that this figure is simply a schematic, and may not necessarily represent the configuration of the final vehicle. The sail is constructed of a thin, light-weight, highly reflective material. Its purpose is to reflect photons that are streaming off the sun, and, in the process, provide a means of momentum transfer to the vehicle for propulsion. The sail is supported by a rigid structure, but the deployment of a mechanical structure of the necessary size would be extremely difficult (and is one of the reasons a sail has yet to be flown). Instead it is proposed that the sail's structure consist of a rigidizing inflatable structure. By its very nature, the inflatable structure would also provide a means for sail deployment.

The rigging is used to control the configuration of the sail, i.e., its angle relative to the sun. By changing the angle at which photons strike the sail, the ship can be maneuvered. For purposes of illustration, the rigging is depicted as a system of cables. On an actual vehicle, however, the rigging would most likely *not* be a mechanical system, but would instead be highly integrated with the sail itself. At present, three examples of such integrated systems have been discussed: solar cells, liquid crystals, and piezoelectric. If the sail were covered (at least partially) by solar cells, the vehicle could be controlled by varying the amount of power drawn from the cells over the sail's surface. By increasing or decreasing the amount of power produced by a given region of cells, the reflectivity of the sail in that region could be varied, changing the propulsive force on the sail. Similarly, by covering the sail with a thin layer of material which include liquid crystal, the sail's reflectivity could be modified in any given region. Finally, piezoelectric material could be included in the sail's construction. By providing an electric current to the piezoelectric material, it could be used to physically "deform" the sail's shape, and thereby provide control.

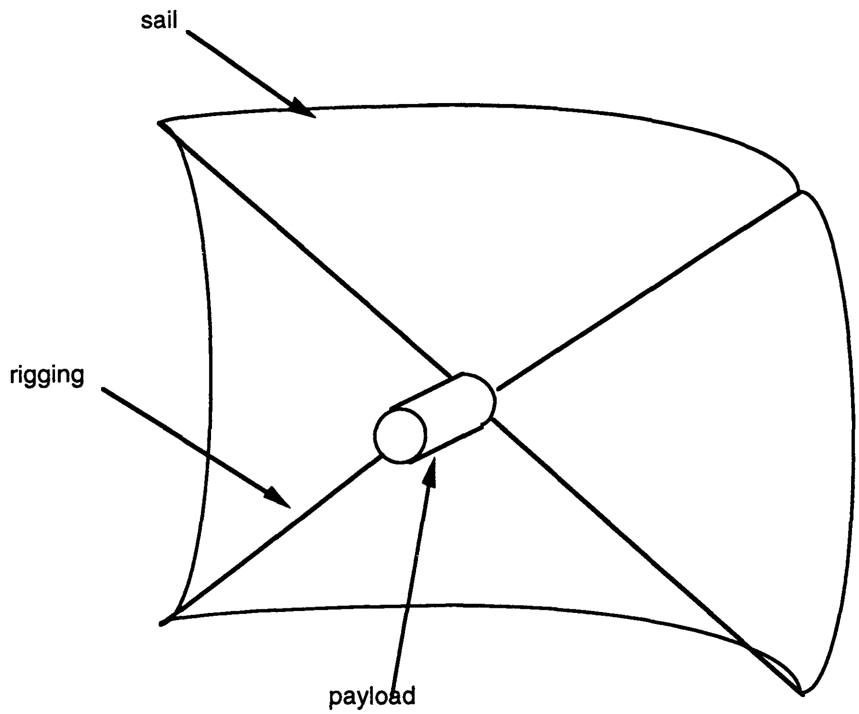

Figure A.1 System Schematic

The final component of the vehicle is the payload, shown in greater detail in Figure A.2. As previously stated, the intent of the demonstrator is to maintain a simple overall vehicle design, allowing for the use of a small sail. The payload, therefore, includes a sail control system (a means of controlling the systems discussed above); a power distribution system; guidance, navigation, and control; a sensor (such as a video camera); and communications equipment.

As previously noted, the demonstrator is intended to be an autonomous spacecraft. Rather than requiring a small army of ground controllers to monitor and control the spacecraft, this vehicle is intended to require no human intervention, except in the case of a severe problem. This feature of the design is in fact dictated by the use of the sail, which would be quite difficult to control effectively from the ground.

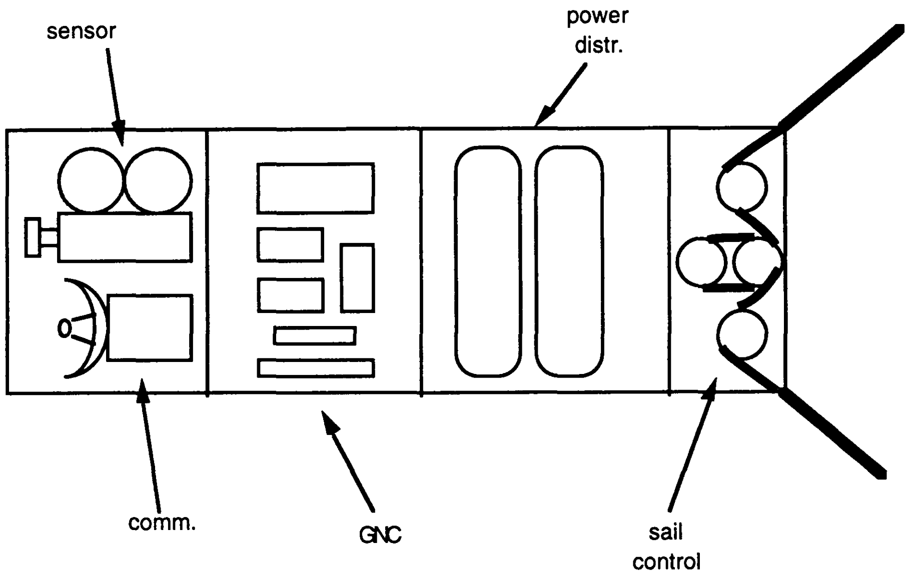

Figure A.2 Payload Schematic

Benefits to Draper Laboratory

Draper would benefit from involving itself in this project. The Laboratory is already well respected in the fields of navigation, guidance, control, micromechanical devices, and equipment packaging. The development of a solar sail demonstrator would make use of all of these skills. While other companies are working on the structure of the sailing spacecraft, there appears to be a gap between such "mechanical" design and the design of the necessary computer systems and their associated packaging for the vehicles. Draper, with its skill and experience in these fields, could readily step in to fill this gap.

While Draper would most likely not manufacture solar sails themselves, after working on the demonstrator, Draper would be firmly established as the leader in solar sail control. Draper Labs would then gain access into the space technology market, a market with a tremendous amount of growth potential. Once Draper has solidified its reputation with solar sail control systems, it is not unreasonable to imagine the Lab broadening its market share by applying its skills in other areas of spacecraft control.

The Laboratory has in fact been involved in several design efforts for micro-spacecraft, but none of these projects has resulting in flying a vehicle. This project would present Draper with the opportunity to do so, enhancing its market standing in the field of micro-spacecraft. Draper therefore stands to not only gain access to a newly emerging technology but to the growing market of spacecraft design and development.

Preliminary Analysis

The Basic Principles

A terrestrial sailboat uses the combination of wind and water for propulsion and steering. The solar sail equivalents are light (photons) and gravity, respectively.

Photons have momentum proportional to their wavelength. This momentum can be used to exert a force on a mirror: this is the basic principle of solar sailing (see Figure A.3). Using Newton's Second Law, the solar pressure on a planar surface is:

$$P = \frac{2W\cos^2\alpha}{cR^2} = 9.126\times10^{-6}\cos^2\alpha \qquad \text{(at 1 AU)}$$

where P is the solar pressure in Pa, W is the power intensity (1368 W/m^2 at 1 AU from the Sun), c is the speed of light, R is the distance to the Sun in AU, and α is the angle between the surface normal and the line from the sail to the Sun [Ref. 2].

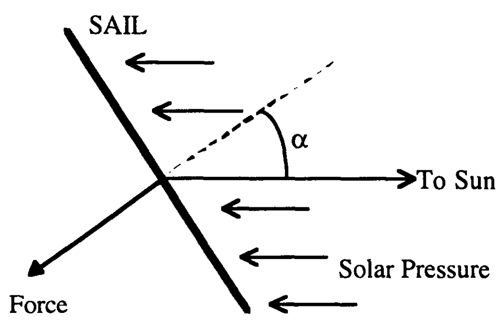

Figure A.3 Solar Sailing Basics

The force of gravity is essential to guide a solar sail (otherwise, it would just be pushed away from the source of light). An advantage of solar sails is their ability to achieve trajectories out of the plane of the ecliptic (a very expensive maneuver with chemical rockets), simply by reorienting the sail.

Sail Design

The solar sail consists of a large lightweight mirror. The shape of the sail could be chosen from a variety of options: square, circular, annular, etc. Each design would require a different control system. The sail loading, σ, is defined as the total mass of the spacecraft divided by the area of the sail. With the current state of technology, a solar sail with a loading of 5 g/m^2 could be achieved [Ref. 2]. The larger the sail loading, the longer the time required to reach a specific point. Hence, reducing the payload weight or increasing the sail size will reduce the travel time.

In the preliminary calculations (see Figure A.4), the weight of the sail was assumed to be 8 grams per square meter, including the structure, based on the estimates in reference 1. In the vicinity of Earth, with a payload of 80 kg, the resulting acceleration is 0.5 mm/s^2. The thickness of the sail could be as low as 8 microns, which would produce a volume of only 0.04 cubic meters.

The Mission

In order to demonstrate the feasibility of solar sailing, the spacecraft would be launched as a secondary payload on a conventional expendable launcher or by the Space Shuttle. The large surface area of the sail would produce a fast decay in a low-Earth orbit due to atmospheric drag. Therefore, the spacecraft would be inserted into a geostationary orbit, where the deployment of the sail would take place.

From GEO, the sail would have an unobstructed view of the Sun almost permanently. The spacecraft would begin accelerating due to the solar pressure, rising to increasing orbital altitudes. After a few months of travel (depending on the size of the sail and the weight of the payload), the spacecraft could reach the Moon or even acquire escape velocity and travel out into the Solar system. Figure A.4 shows an example of a possible mission.

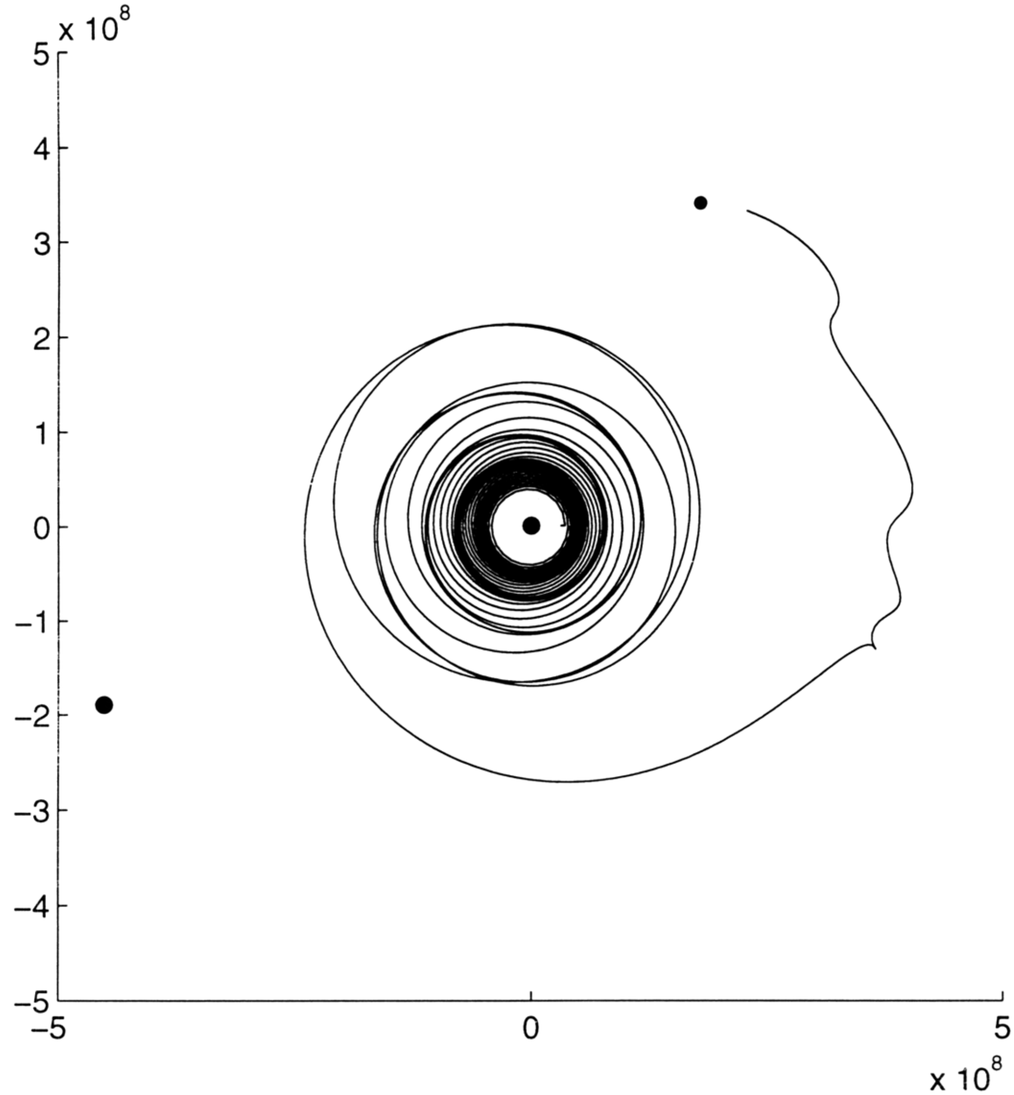

Figure A.4 Numerical simulation of the trajectory of a Solar Sail Spacecraft from GEO to the Moon. Calculations based on a 70x70-meter sail (8 grams per square meter) and a payload of 80 kg.

The Technical Challenges

There are several technical challenges that would have to be met for the success of the project. These challenges include: design for cost (given the limited resources), deployment of a large space structure, control of the sail to achieve an optimum trajectory, and design of an autonomous spacecraft.

Given the high costs of launching a spacecraft and the limited funds available, an important driver for the project would be the design for cost. Using the experience of such programs as the

NEAR Spacecraft from APL and other NASA New Millennium programs, and Draper experience in micro-spacecraft design, the solar sail could be built with a small budget. Where possible off-the-shelf components would be integrated into the spacecraft's design.

A major technical problem is the deployment of a large structure in the vacuum and zero-gravity conditions of space. Related to this deployment is the packaging of the structure so that it could be inserted into orbit by conventional means. An intensive study of the dynamics of flexible structures would be required, but recent experiments onboard the Space Shuttle have shown that flexible structures can be deployed.

In order to avoid the braking effects of solar pressure when traveling towards the Sun, the sail would have to rotate. In general, optimal trajectories could only be achieved by frequent rotations of the sail. The control of the large structure would represent a major challenge that would require imaginative solutions. These solutions could range from the use of microthrusters (which would provide enough torque given the large moment arms), to the construction of the sail as a series of vanes that would rotate separately. This problem also requires a significant software development effort to control the sail.

The design of an autonomous intelligent spacecraft would represent a first-of-a-kind project, since all current spacecraft are controlled from ground centers. The spacecraft would carry an onboard computer that would direct the control system of the sail, based on the reading from various sensors.

Ground Testing Alternative

While the team's preference is to conduct a space-based demonstration of the solar sail vessel, we recognize the significant challenges posed by this goal. In the event that it becomes clear that the team will be unable to conduct a space-based test for technical or other reasons (difficulty in obtaining space on a launcher, for example), it would be possible to conduct a ground-based demonstration. This demonstration would verify the design and operation of a miniature inflation device for the inflatable structure, prove the packaging approach, and validate the overall integration of the spacecraft's systems. Such a ground test would then provide valuable data for future efforts on a space-based demonstration.

Market Assessment

Several potential markets have been identified by the team at this point. These sources are based on telephone interviews conducted by the team with representatives from NASA JPL, private industry, the World Space Foundation, the Planetary Society, and the University of Kent at Canterbury [see note 3].

As to be expected, the short term market for solar sails is dominated by NASA. Within the next five years, however, the National Oceanographic and Atmospheric Administration would like to place a satellite in the Sun-Earth Lagrangian point (L1) to provide additional warning time for solar storms. Since L1 is an unstable point and the satellite would require a long operating life, the only propulsion system that would appear practical is a solar sail. Over the next three to four years there is the potential for several additional vehicles that could make use of solar sail technology. Moving further ahead into the future, NASA is considering such a propulsion system for interplanetary cargo transport, in support of a manned mission to Mars, for example. Additionally, in the spirit of "faster, cheaper, better," solar sails can be an attractive alternative to chemical rockets for interplanetary space exploration, especially missions which require the vehicle to maneuver out of the ecliptic plane.

The design team has also attempted to identify other, less "traditional" markets. One proposed application would be for highly maneuverable satellites in geosynchronous orbit. By attaching a sail to such satellites, the spacecraft could maneuver an unlimited number of times, extending their service lives over similar satellites with chemical propulsion systems. Another potential application might be amusement parks. Several sails could be placed in high orbit above the Earth. Visitors could then be allowed to maneuver the sail in space (while the spacecraft's onboard computers prevented the visitor from sending the sail into the depths of space). The visitor would then be provided with a video sent back from the spacecraft, showing what he commanded the spacecraft to do.

It should be noted that since no solar sail has never actually been used, all of the benefits of this method of propulsion have yet to be explored. It is reasonable, therefore, to expect the market for solar sails to grow as the technology develops. By being the first to fly a demonstrator, MIT and Draper would be able to position themselves as leaders in this market.

A market assessment of this project would not be complete without also considering the field of miniature spacecraft . The idea of "microsats" is only just beginning to develop, but it is clear that such small spacecraft will have applications ranging from telecommunications constellations to interplanetary exploration [ref. 4]. Since the solar sail demonstrator would necessarily include a small satellite-type vehicle, Draper would gain valuable technical and market experience in this field as well. This development work would also provide an excellent follow-on to work already done for the micro-satellite engineering lead project completed last June. While that project resulted in valuable design experience, it did not include the construction of "flyable" hardware. The solar sail demonstrator would build on the design experience of this past lead project, taking Draper to the next step of producing actual hardware components and integrating them into a spacecraft.

In conclusion, the solar sail represents a space technology which is ripe for development. By participating in such a project, MIT and Draper Laboratories would broaden their access to the developing space technology market, establishing themselves as leaders in the specific fields of solar sails and micro-spacecraft design and development.

Endnotes and References

1 - Friedman, Louis, *Starsailing, Solar Sails and Interstellar Travel*, John Wiley & Sons, New York NY, 1988.

2 - Wright, Jerome L., *Space Sailing*, Gordon and Breach Science Publishers, Philadelphia PA, 1992.

3 - This section is based on extensive telephone interviews with the following:

James Garry, University of Kent at Canterbury, November 6, 1996.

Emerson Labambard, World Space Federation, November 12, 1996.

Lou Friedman, The Planetary Society, November 12, 1996.

Costa Cassapakis, L'Garde, Incorporated, November 14 and 18, 1996.

Arthur Chmielewski, NASA Jet Propulsion Laboratory, Inflatable Structures Group, November 18, 1996.

Guy Man, NASA Jet Propulsion Laboratory, Autonomous Spacecraft Group, November 19, 1996.

Charles Garner, NASA Jet Propulsion Laboratory, Solar Sail Group, December 5, 1996.

Bruce MacKinzie, Charles Stark Draper Laboratories, December 9, 1996.

Warren Fitzgerald, Charles Stark Draper Laboratories, December 9, 1996.

Steve Cropnik, Charles Stark Draper Laboratories, December 9, 1996.

The statement of potential NASA funding was made by Arthur Chmielewski.

4 - Robinson, Ernest Y., et. al. "Big Benefits from Tiny Technologies." Aerospace America, October, 1996. pp.38-43.

Appendix B Original Requirements Document

Wide Area Surveillance System Requirements

(Status: 2 January 1997)

• General System Functional Goals:

The non-lethal LISP system goal is to provide local theater commanders with rapid localized reconnaissance information that can be used in a timely manner as an aide to ensure mission objectives are secured. Launched from the sea or from land (see operational scenario), 5-inch or 155mm projectile launchers will be the basic interface for LISP operations. Ideally, LISP's surveillance objectives should be selectable just before launch, while LISP is en route, and during the system's flight data collection and/or targeting mode. Since WASPs are expendable - low cost will be an important design driver. While the primary functional objective is surveillance, LISP's secondary goal is to provide a temporary network of airborne relay stations that can be used for linked line-of-sight communications.

• Range:

70-200 miles from launcher using rocket-assisted projectiles.

• Time aloft after projectile delivery / operating time:

1 to 8-hours and this will depend to some extent on trades made between system performance, complexity, and cost. Operational time: 2-hours.

- Desired surveillance area:

  To be determined as the typical "Area of Action" or operational area for a self-sustained Marine Brigade.

- Projectile diameter / length:

  5-inch or 155mm diameters. Length will be consistent with existing projectiles in this class.

- Location accuracy:

  Several meters.

- Sensor type:

  Primary focus should be on an imaging camera.

- Self destruct mechanism:

  Self destruct will ensure that no piece of the destroyed projectile will exceed the characteristics of an 8-oz can of cat food. For military operations - the flyer will also be designed to self destruct at the end of its useful mission.

- Acquisition cost target:

  Conventional 5-inch and 155mm munitions cost approximately $800. Rocket-assisted projectiles in this class can cost $10,000. The expendable LISP (projectile, flyer, and sensor package) cost should be within the $20,000-$30,000 range in production.

- Information timing:

  Near-real-time.

- Level of autonomy:

  To be determined via system trades.

• Existing physical, political, or organizational constraints:

LISP must be inexpensive to ensure its use in local theater operations.... organic. Projectiles in this class spin at 250 Hz - so a slip obturator (launch shroud) of some type might be required to ensure "near-0" launch spin for LISP

• Environment:

Launch "g"s baseline - 10,000. However, "g"s will increase if trades suggest that the LISP system will result in an integrated projectile with weight less than that of conventional munitions.

• Shelf life:

Approximately 20-years with provisions for replacing batteries and expendables for flyer and communications at pre-determined intervals.

• Existing surveillance MOEs:

Not aware of any at this time. Check with potential customers once design project is underway.

• Covertness level:

The flyer sensor package is expected to be quite small. So an effort should be made to ensure that large flyer components like wings or rotating components like propellers and rotors are of suitable materials to ensure that low RADAR signatures are maintained. Visual and acoustic signatures must also be low.

• Reliability expectations:

90% availability. That is to say - one out of 10 WASPs might not perform as expected.

- Extensibility:

  The primary extension of the LISP concept is to provide a temporary LOS communication network for relaying data and messages. Additional sensor applications, beyond static imaging, for all-weather operations (RADAR?) and chemical/biological sampling should be considered. Acoustic, IR, and motion sensors are also of interest. LISP variants should be adaptable to address civil and commercial needs providing that the system can be adapted to smaller launchers and possibly smaller projectile sizes.

- Prep. and launch time:

  2 to 3-minutes

- Safety issues:

  LISP will be stored in magazines along with conventional munitions. As such, it will have the same or better characteristics as munitions when exposed to mishandling, fire, or detonations.

- Special demonstration considerations:

  LISP will be field tested at the Navy's Test Facility in Dahlgren, Virginia. For the field test, a 70+ mile range will not be required. In addition, it would be desirable to retrieve the test article and as such - no self-destruct mechanism will be assessed during the planned system demonstration period.

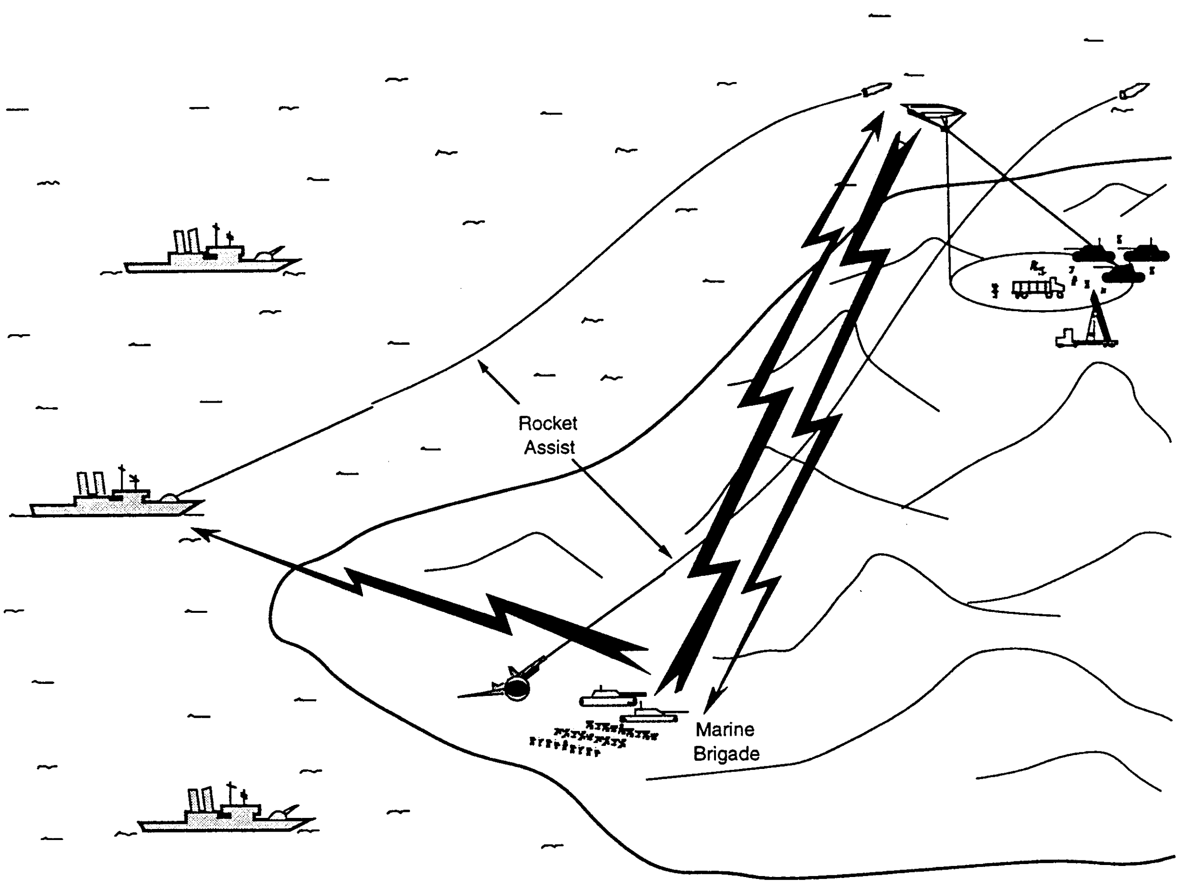

Figure B.1 WASP Operational Scenario

Appendix C Requirements Review Contacts and Interviews

Note: Except where indicated, all interviews were conducted in person by the author.

Bowerman, Randy D., Warrant Officer, United States Army
UAV Systems, Fort Sill

18 Feb 97 (Telephone Interview)

-Forward Line of Troops (FLOT) = 19 - 25 kilometers
- -now using tactical UAVs (Outrider) for this area
- -supports brigade commander

-Worth investigating jamming payloads (electronic warfare) for WASP

-In terms of imaging system:
- -users prefer full-motion to freeze-frame
- -some missions (point surveillance, battle damage assessment) could be freeze-frame
- -if freeze-frame is used -- use 9 second update rate

-In terms of loiter:
- -1 hour is good target
- -shorter loiter time would require lower acquisition cost

-Advantages of WASP:
- -could be used before enemy air defenses are suppressed
- -speed
- -battle damage assessment for ATACMS (new Army missile system) Multiple Rocket Launch System (MRLS), 155mm artillery

Curtis, John

Project Manager, Draper Laboratories (Army Intelligence, Reserves)

14 Jan 97

-Basic Structure of the Army:

1 Corps ==> 3-4 Divisions ==> 3-4 Brigades==> 3-4 Battalions ==>

3-4 Companies ==>3-4 Platoons ==> 3-4 Squads ==> 2-3 Teams ==> 4-5 People

-Interfaces b/w units for artillery fire for the Army:

-1 battery has 6-9 guns (155mm howitzers)

-This battery supports a battalion; they communicate via satcomm or LOS

-At the battalion is an S2 officer and a FSO

-The FSO is the officer who talks to the artillery battery

-The S2 is the intelligence officer who gives information to the FSO

-S2's between battalions can communicate and share information

-System known as ASAS allows for screen captures of video images

-Interfaces b/w units for the Marines:

-basically the same as for the Army, but the battery is replaced by a ship

-ship has its own intelligence capabilities

-How far ahead do units look?

-Division: 75 - 200 km

-Brigade: 50-175 km

-Battalion: up to 75 km

-Company: up to 50-75 km.

-What should our vehicle do?

-Tailor it to the soldier fighting the battle; what is coming next, not hours from now

-Make it "fire-and-forget"; has 1 or 2 preprogrammed flight plans

-Keep the human interface simple; make the vehicle think so that men do not have to be extensively trained

-For the Army, send the data from out vehicle straight to the S2 at the battalion level and then let him pass it on to the howitzer battery

-For the Navy/Marines, send the data back to the ship, then pass it on to the Marines

-Might consider a hand-held display/comm. system so data can be displayed to a platoon or squad -- look into APPLIQUE

-Send freeze-frame images, not full motion

- Could it have the ability to read IFF codes?

-Scenarios -- When will this thing be used?

    -Cued by other assets (as a UAV is going to its patrol area, it sees something of interest to a company commander)

    -Called on by a company just before it moves (i.e., get a picture of a breech sight just before the unit moves)

    -Battle damage assessment (BDA) for artillery

    -Special Forces BDA

    -Might fit in very nicely with the "Arsenal Ship"

-For Comparison: Outrider UAV

    -Important Information: 5 hr loiter, 200 km range, $300-500,000, controlled at company level, information sent to brigade level

-For Further Investigation:

    -ASAS: Army system to do image captures

    -AITR: Automatic target recognition of targets through video images; work being done on this system at Draper

    -FORCE 21 -- APPLIQUE: System to disseminate information between units

Entzminger, John

Director, Advanced Development Division, Defense Airborne Reconnaissance Office (DARO)

and

McDonald, Randal

Senior Systems Analyst, Science Applications International Corporation (SAIC)

12 Feb 97 (Joint Interview)

-Tactical Control System (TCS)

- -common ground station for UAVs
- -will be used with Predator and Outrider UAVs first
- -will have vehicle control, communications, data analysis

-Regarding frequency of image transmission: could wait minutes but not tens of minutes

-Value of WASP is *timing* -- high-value, quick, "no other way to get there"

-Outrider UAV controlled at the division or brigade level

- -will cost more than $300,000 per airframe, but each airframe should last for about 100 missions

-Our cost of $30,000 per vehicle for WASP is high

- -would be better if WASP cost more around $3,000-$5,000

-Drawback of WASP is short time on station

-Regarding desired image resolution:

- -should be about 1-meter; good enough to distinguish a car from a Hummer

-Raised concerns about all-weather capabilities (or lack thereof)

- -suggested investigating use of infrared sensors
- -look into Sense and Destroy Armor munition (SADARM), and the Brilliant Anti-tank Weapon (BAT)

-Might want to look into launching from the Multiple Rocket Launch System (MRLS) -- might be cheaper; softer launch (i.e., lower impulse than an artillery gun)

-Search pattern issues:

- -pattern varies based on the sensor used
- -better off knowing GPS coordinates of target than vehicle collecting the information
- -search is limited due to narrow field of view of most sensors

-Regarding possible missions:

- -Signals Intelligence:

-would have to be all-weather
-usually done better at longer range/stand-off
-not a particularly good option for WASP

-Chemical/Biological Weapons Detection:
-might be a good mission for WASP
-clouds tend to dissipate quickly ==> need to get a sample quickly
-but, might work better as a mortar

-Imagery
-best mission option for WASP

Miller, Judy
UAV Systems, Draper Laboratory

9 Jan 97

-Discussion focused on the mission

- -"your vehicle is a dumb truck" ==> need to understand it's mission ==> who is is using it, and for what
- -goal is to get data from the payload to someone who can use it
- -how much time is there to process the data?
- -comm link is critical
- -Depending on comm restraints, may need to do a lot of processing on the vehicle
  - -Location, orientation
  - -Target ID
- -Use a digital sensor -- better data comm.
- -may not need to constrain launch time so much -- why is it so constrained?

-Regarding the 2 year demo:

- -establish lower tier or reduced set of requirements for a demo system
- -understand the relationship between the demo system, the engineering system (i.e., operational prototype), and the operational system

Scott, Porter, Chief Warrant Officer, Second Class, United States Army
UAV Systems, Fort Huachuca

19 Feb 97 (Telephone Interview)

-General reaction to project: "You gonna have troubles"

-Working on a similar system for the Army; contracted by Picatinny Arsenal for this work

  -not using propellants in the gun

  -32 km. minimum range

  -real-time, freeze-frame imagery; one image every 2 seconds

  -cost of about $5,000 per round

Turner, John, Lieutenant Colonel, United States Marine Corps
MIT Defense and Arms Control Studies Military Fellow

and

Trahan, Michael, Colonel, United States Army
MIT Defense and Arms Control Studies Military Fellow

15 Jan 97 (Joint Interview)

-Discussed scenarios:

- -Point Surveillance -- ex: 4-5 avenues of entry into your area; need to know movement of enemy forces (maybe 8 hr. endurance)
- -Route Reconnaissance -- ex: fly along a straight route (maybe a road) to patrol it before a unit moves through
- -Counter-battery fire -- possible, but radar systems already do this.
- -Area Reconnaissance: survey as large an area for as long as possible
- -Last look before moving -- fire one of these off before a division begins to move
- -Battle Damage Assessment (BDA) for naval gun fire
- -Suggested it would be good if we could get our loiter time up to about 6 hrs., with as long an operational time as possible
- -In summary: trade b/w range and loiter
  - -go 200 km, look at point (no loiter - short loiter)
  - -go 70 km, loiter for 6 hours
- -more is better!

-In terms of who would control this vehicle, suggested it would report to the brigade commander, assuming corps and division commanders have access to UAVs; this means our system would be controlled at the regimental level

- -To accomplish missions at the company level, the vehicle could not cost any more than $10,000 a piece.

-Areas of control by unit:

- -Company -- out to 5-10 km, with a 1-12 km "box" for movement
- -Battalion -- out to 30-50 km
- -Brigade -- out to 50-75 km
- -Division -- out to 100+ km
- -Artillery usually fires out to 50-75 km.

Zimerman, JB
DACS Graduate student

8 Jan 97

-General discussion of military gun systems:

- -3 main types of guns: mortar (highest arc, lowest speed), howitzer (middle arc, medium speed), cannon (direct higher, high speed)
- -155mm towed howitzer: 3-5 crewmen, rifled gun, external targeting system
- -self-propelled 155: called the "Paladin", basically the same as a towed 155, but mounted on an armored vehicle, has its own targeting computers.
- -regarding rocket assisted shells: rocket is part of the traveling shell, so it reduces the payload.

-discussed operational doctrines

- -when artillery shoots, usually fires 1-2 ranging rounds, then shoots to kill on 3rd round
- -3 batteries in a brigade, one is "shooting," another is "scooting," and the third is "prepping" ==> one battery is operating at any given time
- -Usually fire in "battery 3" or "battery 5", i.e., all guns fire 3 or five rounds

-discussed handling issues:

- -avoid protrusions
- -155mm can usually fire 3-5 rounds/min

-discussed intelligence assets; our systems competitive advantage would be if we could give an intelligence. capability to small sized units (currently intelligence. is at the division level)

Appendix D Functional Flow Variants

After the baseline functional flow diagram was developed, several additional versions were created. These FFDs addressed different aspects of the design, some attempting to simplify the design, others attempting to add features which might delight the customer. The diagram for each variant is shown on the following pages after the brief descriptions given here.

- Communications Relay Variant: This version was developed to fulfill the communications relay mission. The only changes made to the FFD were in the mission segment loop, so only these modifications are shown.
- Hunter Variant: Developed for the Hunter mission, this variant included several changes to perform the needed functions. This version was capable of designating targets, but it was not intended to attack those targets.
- Hunter/Killer Variant: This FFD is essentially the same as the Hunter Variant, but this version includes the needed functions to allow the vehicle to attack the target which it has found.
- No Active Control Variant: This variant was developed in the event that there were development problems with the autonomy systems or if they became prohibitively expensive. This FFD contains no functions which relate to controlling the vehicle. The ground station cannot transmit any commands to the flyer, nor can the flyer alter its own flight path. The vehicle was to be designed to be stable and to enter a simple circular search pattern using fixed deflections of its flight control surfaces. It would be programmed before launch with mission parameters, such as how often to take pictures, but once launched, the vehicle's operation could not be altered in any manner.
- No Ground-to-Flyer Variant: Another variant intended to simply the system, this FFD showed the alterations that would occur in the event that a one-way datalink was used. Note that the mission segment of the baseline FFD was not altered for this variant, so that portion of the FFD is omitted.
- Send Program Variant: The Send Program Variant showed how the functional sequence could be altered to speed up the mission preflight. Rather than loading the mission into the vehicle prior to launch, this FFD suggested that the mission plan be transmitted to the flyer once it was in flight. Since this change did not affect the mission segment of the FFD, those portions are not shown.

- Signals Intelligence Variant: This variant was developed to show the functional changes that would result for the signals intelligence mission. Since these changes only addressed the mission segment of the FFD, only this portion is illustrated.

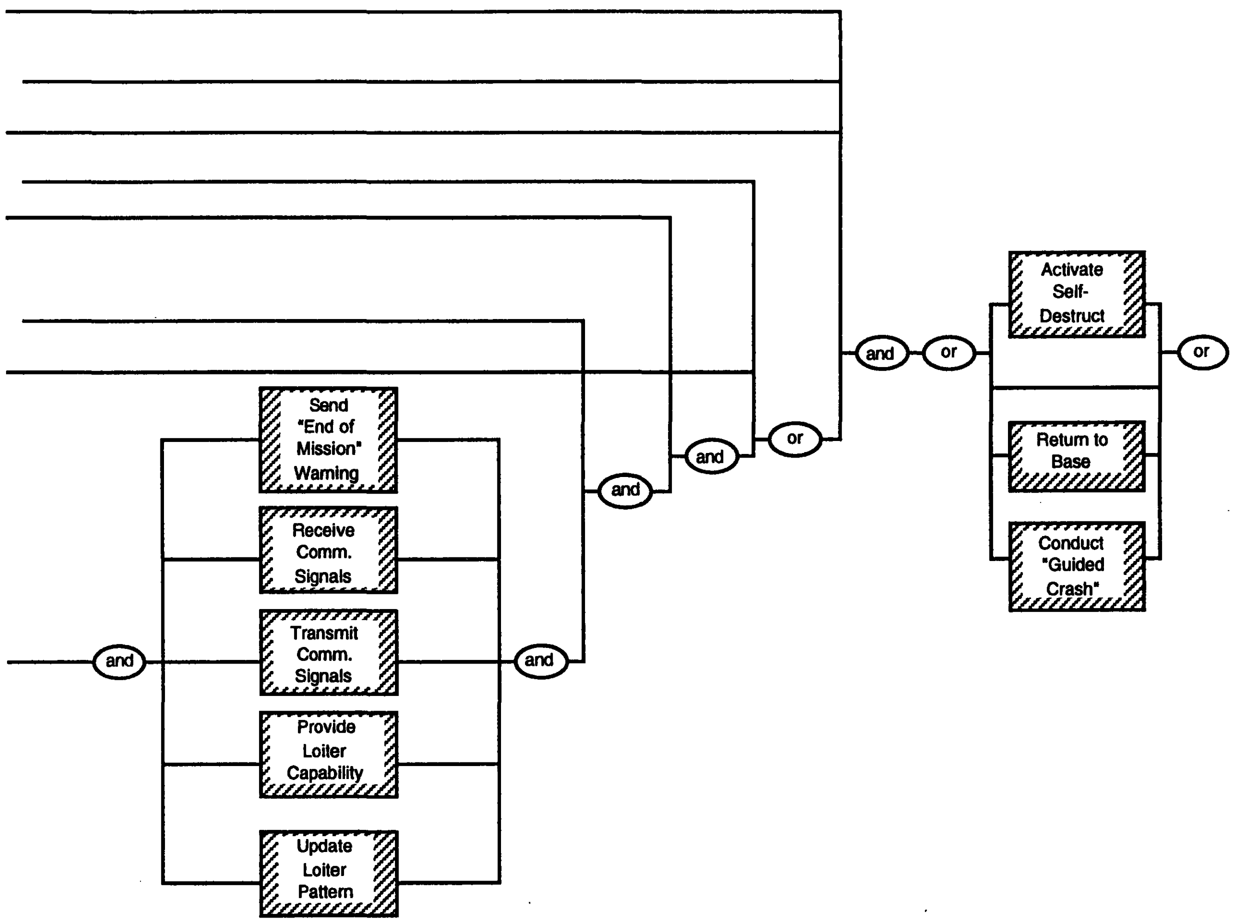

Figure D.1 Communications Variant

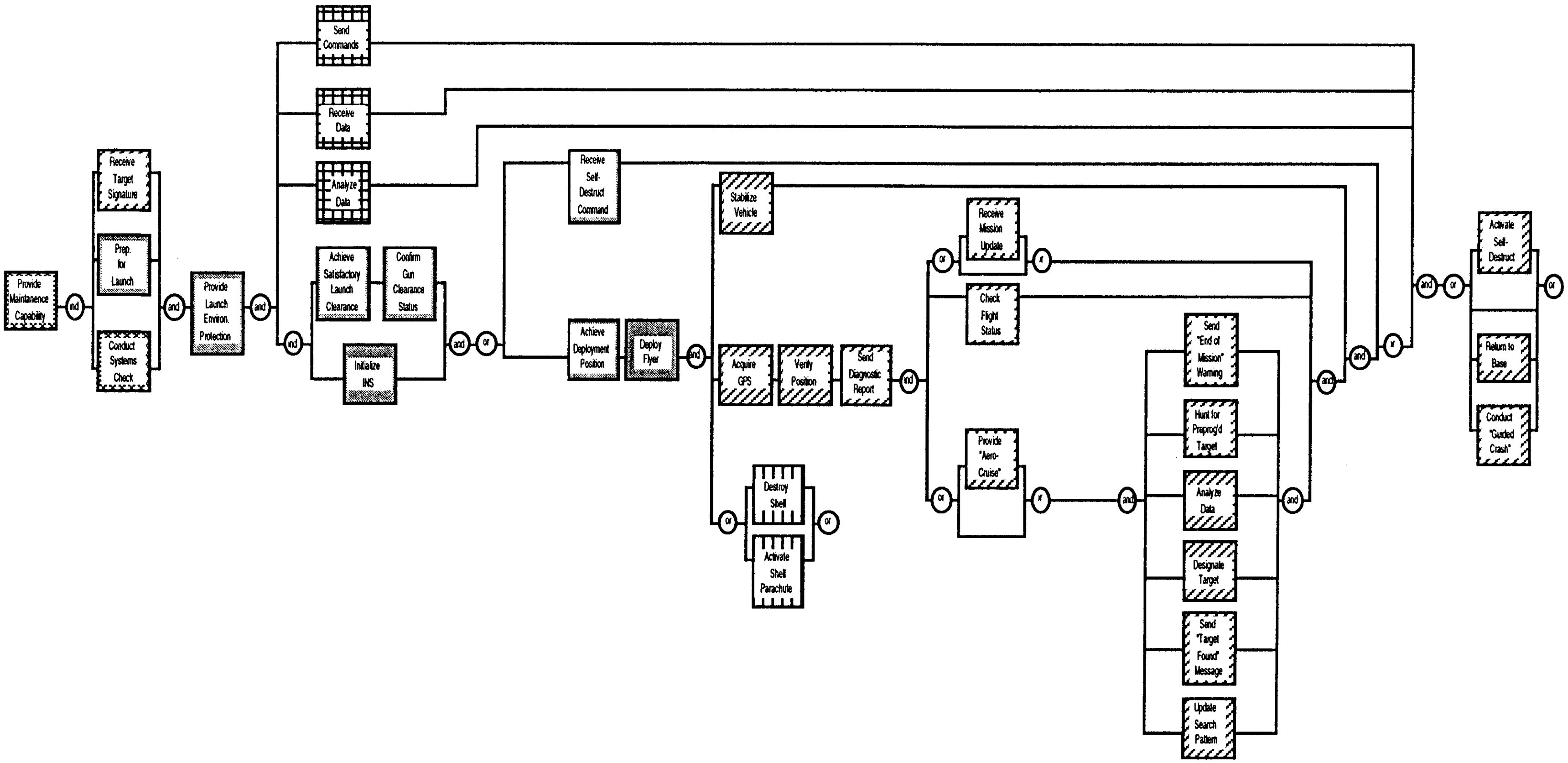

Figure D.2 Hunter Variant

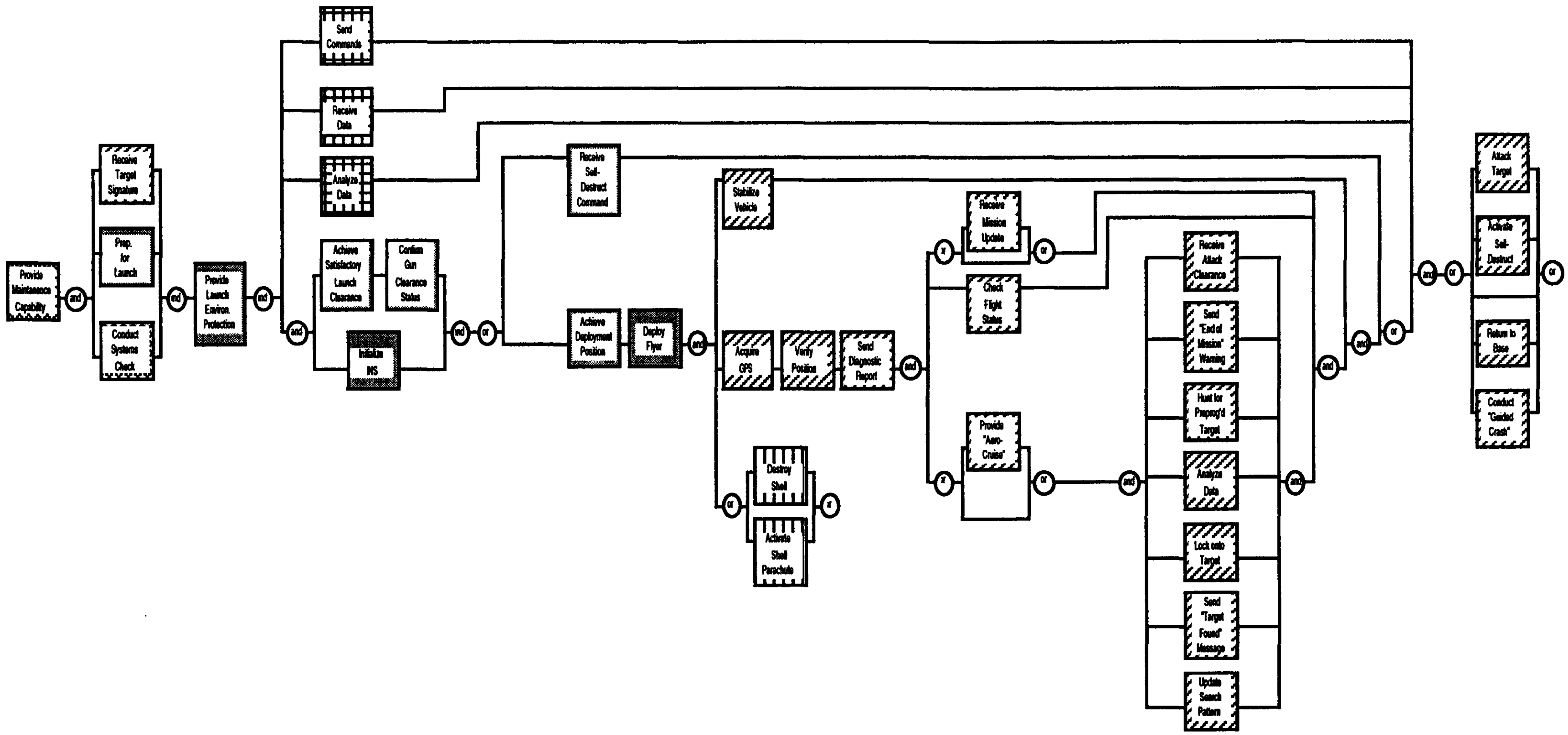

Figure D.3 Hunter/Killer Variant

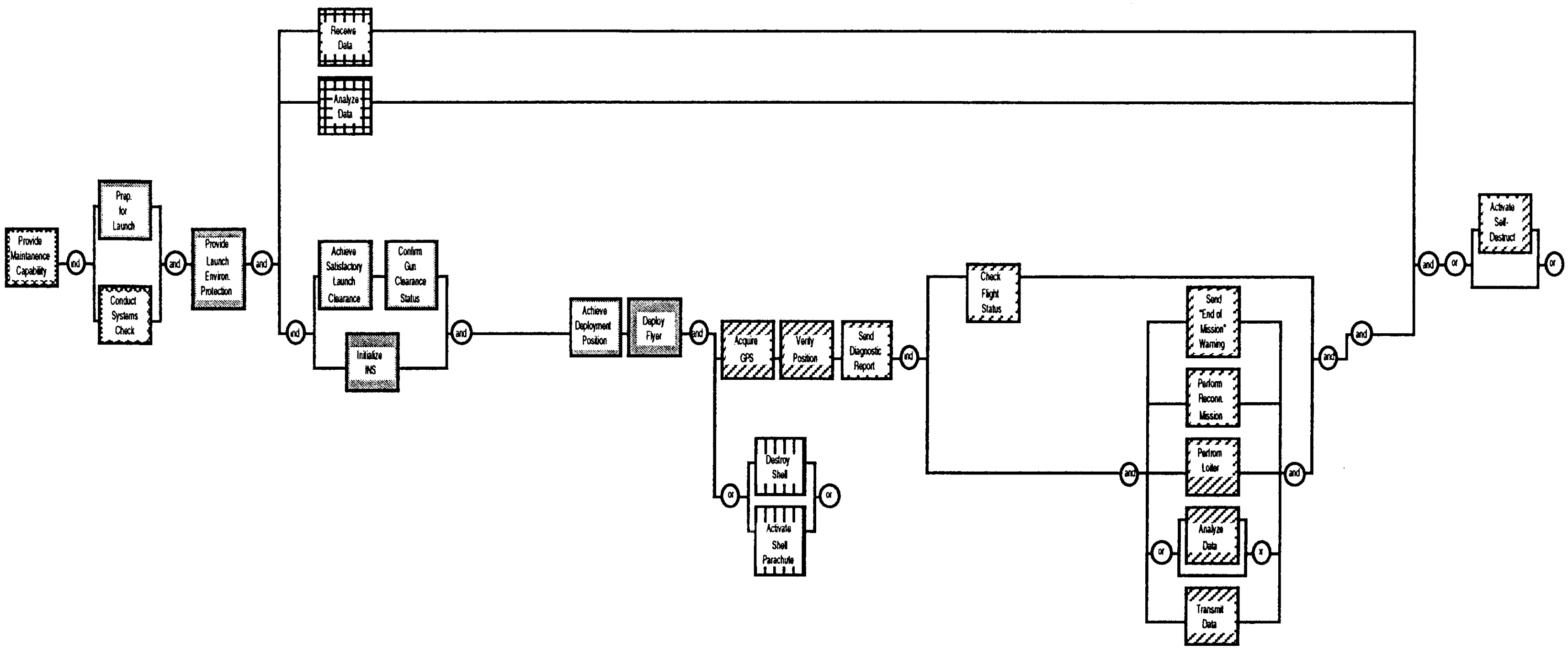

Figure D.4 No Active Control Variant

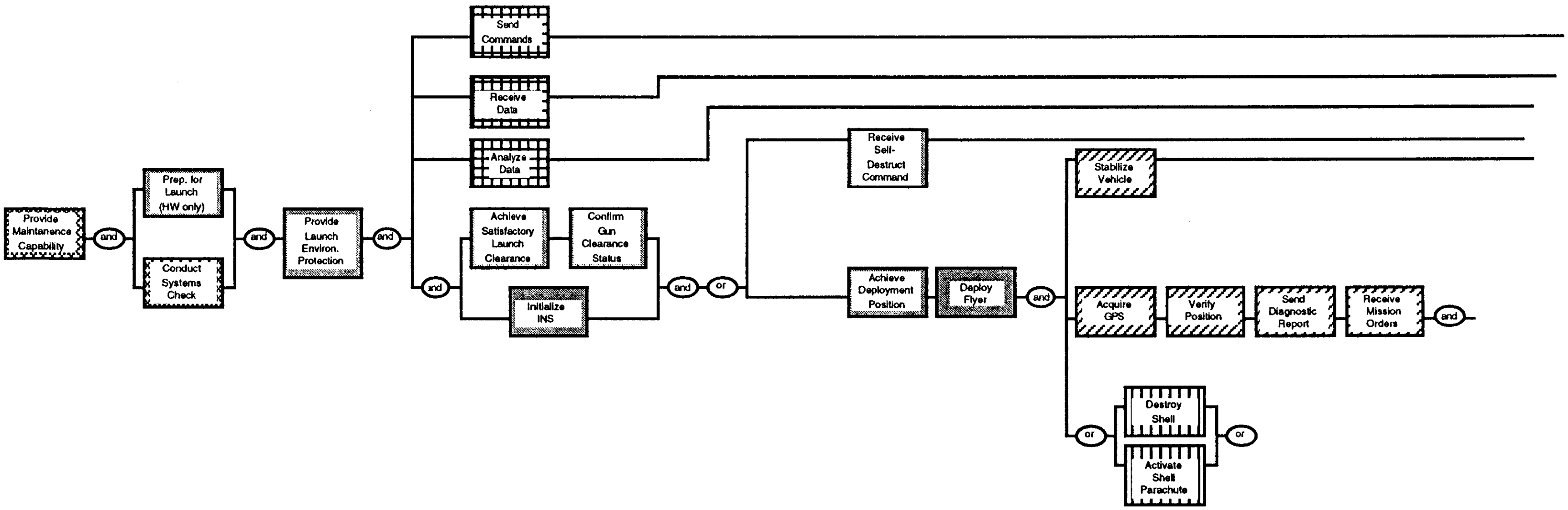

Figure D.5 No Ground-to-Flyer Communications Variant

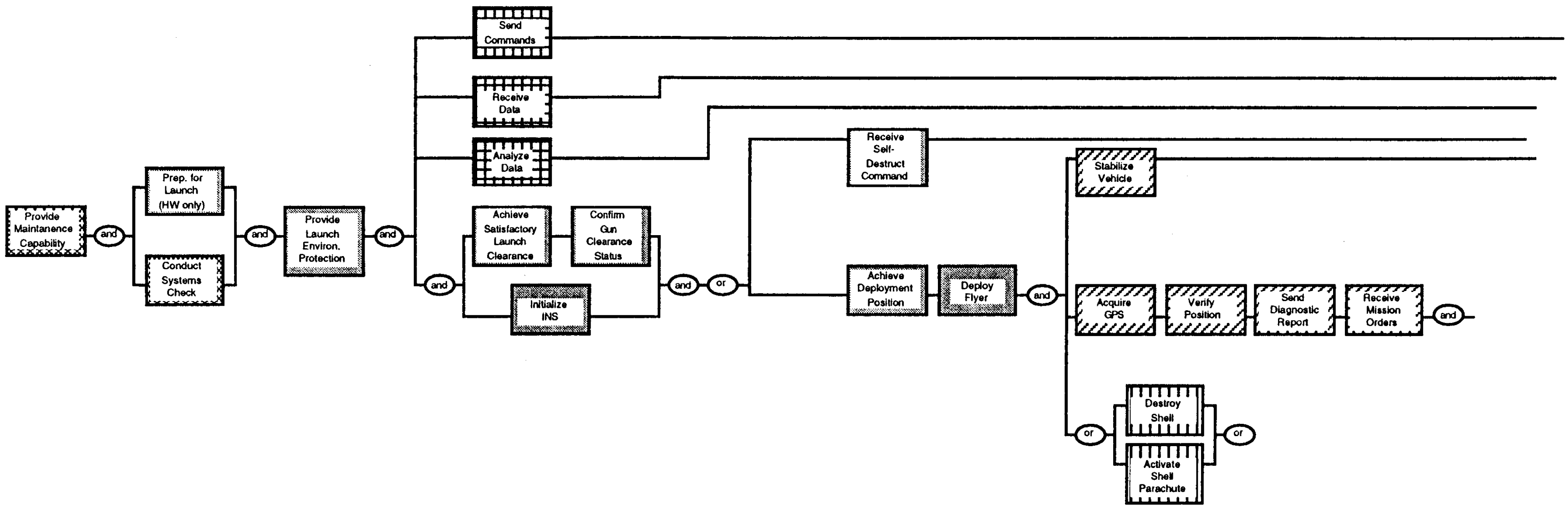

Figure D.6 Send Program Variant

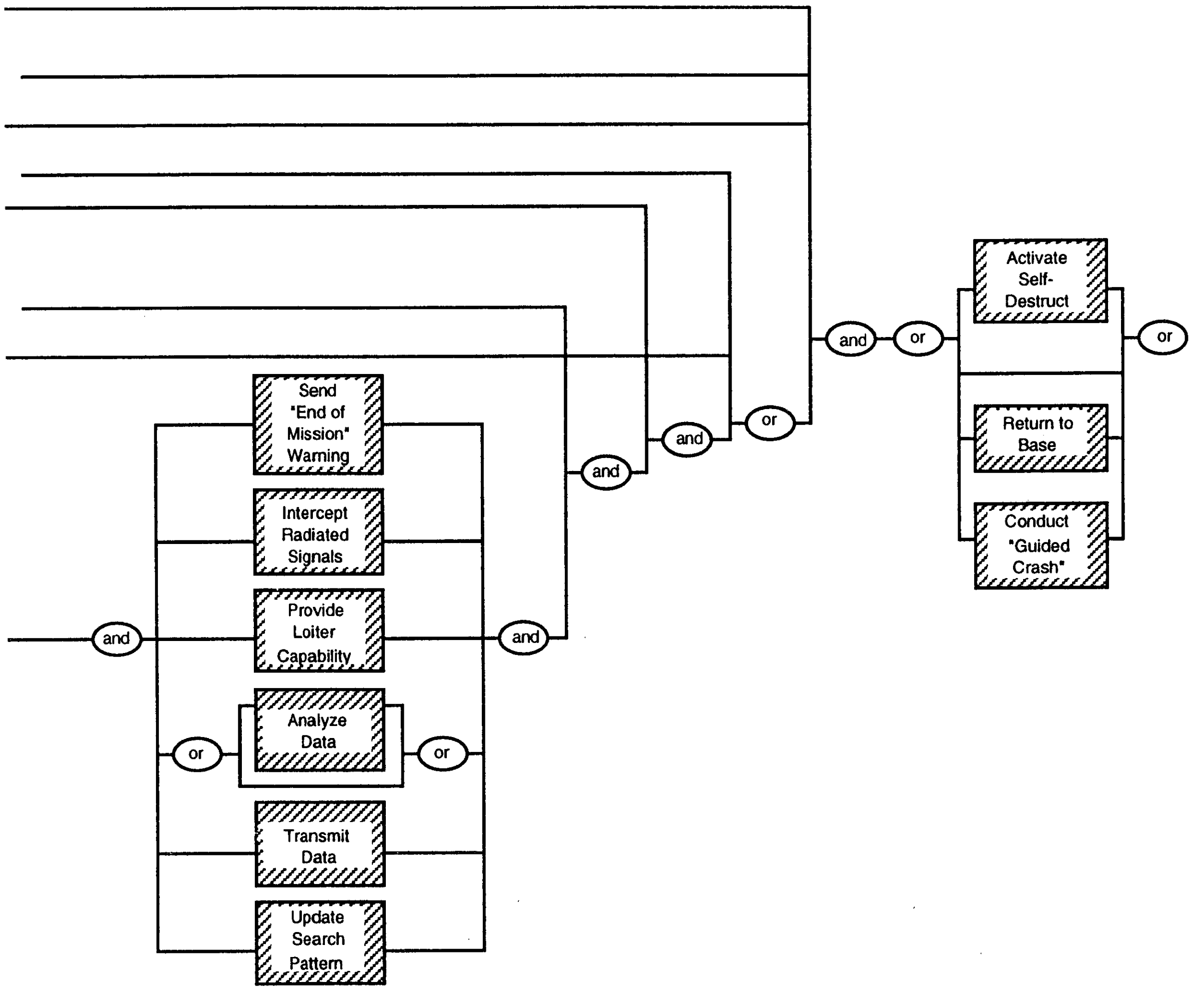

Figure D.7 Signals Intelligence Variant

Appendix E Example Component Table

The following sheet is an example of the component table used by the design team to help develop the WASP flyer concepts. Note that not all of the data for each component is listed. These omissions are the result of the preliminary nature of the work that was being done at the time this table was generated. The component table is a living document, however, and will updated as the design progresses.

Attributes

Component	Person	Cost ($)	Weight (g)	Primary X-Axis (cm)	Primary Y-Axis (cm)	Primary Z-Axis (cm)	Volume (cu. cm.)	General Shape	Ixx (g mm^2)	Iyy (g mm^2)	Izz (g mm^2)	Drawings Received
Sensor	Tan											
COTS/Non-high g (Edmund Sci. Cat # A53,308)	Tan	350 (Catalogue)	14.5	3.2	3.2	2	20.5	Box	1720	1720	2475	Yes
"Projected" Xybion	Tan		340	4.5 (radius)	4.5 (radius)	7	240	2 "stacked" cylinders	206850	206850	344250	Yes
Xybion standard	Tan	<20,000 (high vol purchase)	560	4.5 (radius)	N/A	7	445	Puck	512150	512150	567000	Yes
Comm. Antenna	Matt											
Patch Antenna	Matt		110	5	5	0.5	12.5	Square Patch				
Comm. Equipment	Matt											
Receiver Processor (all estimates!)	Matt		40.2	6.9	3.6	1.02	25.1	Thin Rectangle				No
Transmitter	Matt		85.05	2.22	3.81 (dia)	N/A	25.31	Puck				Barnard
Motor	Ted											
Astro Cobalt 05 (electric)	Ted		198.5	7.62	3.81 (dia)	N/A	86.88	Cylinder				
Astro Cobalt 15 (electric)	Ted		226.8	7.62	5.08 (dia)	N/A	154.4	Cylinder				
Astro Cobalt 05G (electric)	Ted		255.2	7.62	5.08 (dia)	N/A	154.4	Cylinder				
RII C 15 (2-stroke)	Ted											
HT V 21 (4-stroke)	Ted											
[illegible] (rotary)	Ted		[illegible]	[illegible]	7.09 (dia)	N/A	[illegible]	Cylinder				
OS 0.40FX (2-stroke)	Ted		[illegible]	6.35	3.81	6.35	[illegible]					
OS FS-52S (4-stroke)	Ted		402.3	7.62	3.81	7.62	221.2					
Thunder Tiger (Gas engine)		100	179	4.763	3.81	6.033	109.5	Cylinders at an L configuration				
Propeller	Ted											
"Smaller" Prop	Ted			2.54 (chord)	17.8 (span)	N/A						
"Larger" Prop	Ted			2.54 (chord)	25.4 (span)							
Battery/Fuel	Ted											
For battery and fuel information, please see attached chart	Ted											
Power Distribution & Conditioning	Ted											
Power Converter	Ted		~300	7.62	7.62	1.27	73.74	Box				No
FCS Sensors	Dave											
Altimeter	Dave											
Airspeed Sensor	Dave											
FCS Actuators	Dave											
ACX piezoelectric actuator	Dave	(free for us?); ~300 for all controls on one flyer	7.7 g/cc	variable	variable	variable	variable	conforms to design of control surface				Yes
Namiki 18 (stepper motor)	Dave	60 (but min. purchase of 50)	44	6	1.6 (dia)	N/A	15.3	Cylinder				Yes
GNC Systems	Vlad	$105,000 initial, 1 complete GNC; 4000-860 mass prod	112									
Processor Board (2 must be used)	Vlad		40.2	6.9	3.6	1.02	25.1	Thin Rectangle				No
Accelerometers (3 must be included)	Vlad		9.8	3.1	3.1	0.7	6.14	Box				Yes/but its obvious
GPS Receiver (included on boards above)	Vlad											
GPS Antenna	Vlad											
Gyro (3 must be included)	Vlad		14.3	3.8	3.6	0.7	8.55	Box				Yes/but its obvious
Wiring	Cory											
Other Cabeling	Cory											
Wing Design	Dave											
Control Surface Design	Dave											
Data Encryption Processor	Vlad											
Deceleration Parachute	Cory											
Self Destruct Mechanism	Stad											
TFCS (smaller one)	Stad		850	3.1	0.75 (dia)	N/A	1.3	Cylinder				Basic Shape
DEFC-47 (larger one)	Stad		1300	5.6	0.95 (dia)	N/A	4.1	Cylinder				Basic Shape

Component	Peak Power (W)	Peak Voltage (V)	Peak Current (milliamps)	Nominal Power (W)	Nominal Voltage (V)	Nominal Current (milliamps)	Min. Temp (celsius)	Max. Temp (celsius)	Performance Measures	Interface Requirements (ie, wire type)	Additional Notes
Sensor											
COTS/Non-high g (Edmund Sci. Cat # A53,308)				0.81	9	90	-10	50	FOV: 45x34 degrees, Resolution: 0.08x0.1deg, see attached chart	Power Input (two wires, grnd + signal); TV out (two wires, grnd + signal)	NOT HIGH G RATED!!
"Projected" Xybion							-10	50	FOV: 13 deg (Circular); Resolution: .00048 rd, see attached chart	Power Input (two wires, grnd + signal); TV out (two wires, grnd + signal)	Numbers are project by Tan, not confirmed by Xybion!
Xybion standard							-10	50	FOV: 13 deg (Circular); Resolution: .00048 rd, see attached chart	Power Input (two wires, grnd + signal); TV out (two wires, grnd + signal)	
Comm. Antenna											
Patch Antenna				0	0	0			50 Ohm	SMA Connectors to TX	Must be pointed up
Comm. Equipment											
Receiver Processor (all estimates!)											All physical properties are estimated using other processor board values!
Transmitter			200	3.5	17-32				Power output: 200 mA	SMA Connectors to antenna, solder pins for power	
Motor											
Astro Cobalt 05 (electric)				180		30000			Thrust: 5.34N		
Astro Cobalt 15 (electric)				260		30000			Thrust: 8.45N		
Astro Cobalt 05G (electric)				180		30000			Thrust: 6.67N		
RII C 15 (2-stroke)											
HT V 21 (4-stroke)											
[illegible] (rotary)											
OS 0.40FX (2-stroke)											
OS FS-52S (4-stroke)											
Thunder Tiger (Gas engine)									Thrust: 266.3W	Requires liquid fuel and lines, fuel tanks	
Propeller											
"Smaller" Prop											
"Larger" Prop											
Battery/Fuel											
For battery and fuel information, please see attached chart											
Power Distribution & Conditioning											
Power Converter	N/A	N/A	N/A	N/A	5	N/A	-20	60	Conversion efficiecy = 80%	power in and out	No commercial component fits our requirements -- we will have to design and build this device!
FCS Sensors											
Altimeter											
Airspeed Sensor											
FCS Actuators											
ACX piezoelectric actuator	1-3	0-200	dependent on voltage	-	-	-	-57	100	see attached chart (cm bending/volt applied)	voltage	
Namiki 18 (stepper motor)	2.5	3,6,9, or 12	990				-10	60	17 g-cm torque	power (regulated)	
GNC Systems											
Processor Board (2 must be used)				8.65 (32)	5	1730			DSP: TMS 320C31, 32 bit wordlength, 22 MHz, 11 MIPS, 128K x 32 SRAM, 512 x 8 EEPROM	Serial ports for processors; power	Must include BOTH boards in design; weight estimated using density of 1.6 g/cc
Accelerometers (3 must be included)				0.77	12	64			see attached chart	A/D conversion board; power	Must use THREE (3) accelerometers, mounted 90 degrees to each other!
GPS Receiver (included on boards above)									Direct P(Y) acq., 12 channels, 1 Hz update, pseudo-range sigma=1.5m, delta range sigma=2cm, INS aiding, trajectory aiding, jammer aiding	Mounted on board, Antenna interface	This is a component on one of the processor boards listed above
GPS Antenna											
Gyro (3 must be included)				0.77	12	64			see attached chart	A/D conversion board; power	Must use THREE (3) gyros, mounted 90 degrees to each other
Wiring											
Other Cabeling											
Wing Design											
Control Surface Design											
Data Encryption Processor											
Deceleration Parachute											
Self Destruct Mechanism											
TFCS (smaller one)						500	176.7		Resistance 1.5 ohms	Tinned Copper Wire	We're still finding out more info on these
DEFC-47 (larger one)						500	176.7		Resistance 55 ohms	Tinned Copper Wire	We're still finding out more info on these

Figure E.1 Example Component Table

Appendix F Architectural and Flyer Configuration Variants

Architectural Variants

The architecture shown in Figure 4.9 was taken as a baseline from which to derive three variants. Two of the variants were intended to address the issue of beyond line-of-sight (LOS) communications. While the baseline architecture used communication satellites to achieve beyond LOS communications, the team felt it was worthwhile to have an alternative to relying on these systems. The third variant also addressed the beyond LOS issue, but also proposed a new way of partitioning system functions.

Architectural Variant 1: Shell Deployed Communications Relay Balloon

Rather than relying upon communications satellites, an alternative architecture proposed that a balloon be carried along with the flyer inside the shell. When the flyer deployed from the shell, it would also deploy a balloon. Integrated into the surface of the balloon would be a communications antenna. Hardware for the antenna would be either contained inside the balloon, or, if the electronics were small enough, incorporated onto its surface. The intent of the balloon design was that it would draw heavily upon so-called inflatable systems being developed for use in space.

Once the balloon inflated, it would rise above the altitude of the flyer, and then serve as a communications relay between the flyer and the ground. The advantages of this system were that it would reduce the needed transmission power for both the flyer and the ground station (compared to a satellite system) and the system would be entirely self-contained. In this arrangement, rather than having to interact with an external system for communications, the balloon would enable the communications system to reside completely within the WASP system boundary.

Despite these advantages, however, this architecture proved unattractive. The most significant drawback to the system was feasibility -- initial calculations indicated that the amount of gas which would have to be carried inside the shell would exceed the volume that was available. Additional concerns centered around the reliability of the balloon as a communications node. Given that it would not have any active control, it seemed possible that the balloon might drift out of range to be useful.

Architectural Variant Number 2: Balloon Relay at the Ground Station

Another attempt to address concerns related to beyond LOS communications, this architecture replaced the communications satellite with a balloon attached to the ground station. Unlike the free-flying balloon in the first architectural variant, the balloon in this variant would be physically tethered to the ground station.

This design was seen to have many of the advantages of the first variant, without the drawbacks associated with carrying the balloon in the shell or allowing it to drift. The primary disadvantage of the design, however, was that it added equipment to the ground station, something the design team wanted to avoid for several reasons. The first was mobility. The WASP system was intended to be used by small units. Such units are often highly constrained in how much equipment they can transport, thus adding hardware to the ground station was considered undesirable. Additionally, more hardware on the ground would require additional training of ground personnel, both in the deployment and recovery of the balloon and its operation. Finally, as the communications analysis progressed, it became apparent that satellite communications would be feasible. The advantages offered by a tethered balloon, therefore, did not seem as significant[25].

Architectural Variant 3: Twin Flyers

The final architectural variant developed by the team was one which called for one shell to deploy two flyers. One flyer would be equipped with a sensor but only very basic equipment for flight control and navigation and short range communications. The second flyer was to be equipped with all of the systems for advanced navigation, a short range communications system to communicate with the other flyer, plus a long range communications system to communicate with the ground station. Flying at a higher altitude, this second flyer would enable LOS communications with the ground station even while the sensor-equipped flyer was out the line-of-sight of the ground station.

This architecture seemed to possess several advantages over the baseline. The first was the beyond LOS communications without the reliance on satellites (an advantage that was minimized once such satellite communications were shown to be feasible). An additional advantage which the system seemed to possess was flexibility. For instance, it seemed as though it would be possible for one shell to be launched which contained one sensor-equipped shell and one which contained

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[25] More details regarding the various trades considered in the design of the communication system can be found in Matthew Burba, *System Design and Communication Subsystem of an Innovative Projectile*, Cambridge: MIT Press, 1997.

the long range communications systems. A second shell could then be fired containing two sensor-equipped flyers. So long as all three flyers operated near the communications relay, all three could share the same relay. Thus the system offered the potential to triple the area reconnoitered by the flyers while only doubling the number of shells needed to deploy the system.

The major drawback seen to this architecture was complexity. The number of components in a given shell would basically double, the deployment sequence would almost certainly be more complex than the baseline's, and the system's operation would be more complicated (by the need to operate two UAVs in place of one). Despite these drawbacks, the advantages offered by the system seemed to warrant further development, and the configuration derived from this architecture is described below.

Flyer Configuration Variants

Three different flyer configurations emerged from the Tiger Teams which were further developed by the Mini Teams. The two concepts which were not chosen for further developed are briefly described here.

Configuration Variant 1: Twin Flyers

The first variant called for the shell to split into two flyers, one to conduct the reconnaissance mission and one to serve as a two-way communications link between the reconnaissance flyer and the ground station. The system's basic operation is shown in Figure F.1, while the flyer configurations are shown in Figure F.2.

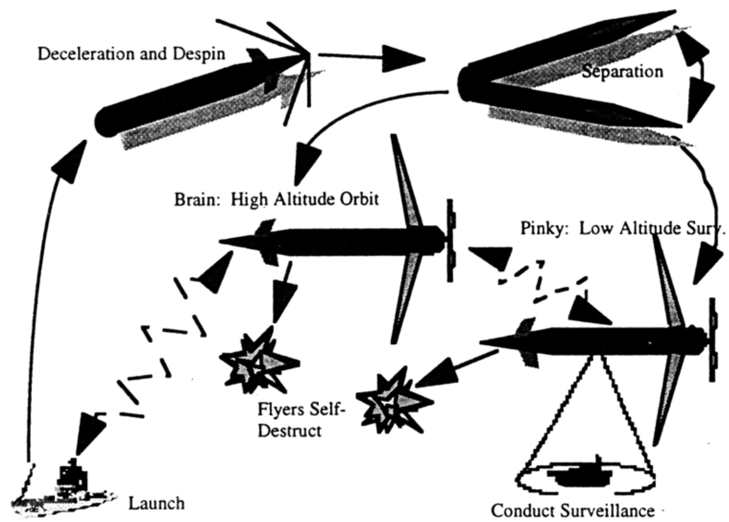

Figure F.1 Twin Shells Deployment Sequence

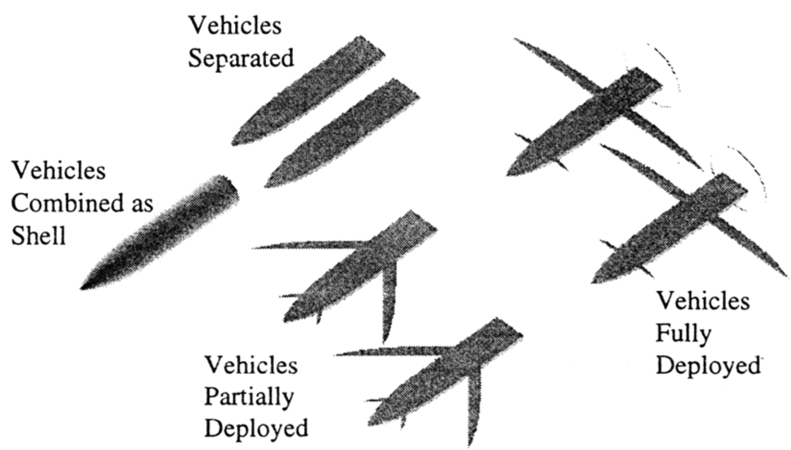

Figure F.2 Twin Shells Flyer Configuration

As shown in Figure F.2, the basic layout of each flyer is the same. The differences between the two are all internal, at the component level. The sensor-equipped flyer contains a sensor and the associated processing equipment, along with a short range communications system. The communications relay flyer contains a long range communications system in place of the sensor, and also carries a short range system to use with the other flyer.

Another feature of this twin flyer configuration was the distribution of functions between the flyers. Because space was so limited on each flyer, not all of the equipment necessary for two completely autonomous flyers could be contained inside the volume of one shell. To get around this problem, the design proposed that many of the functions related to autonomy and navigation be installed in the communications flyer only. This flyer, while cruising at a higher altitude, would then control the sensor-equipped flyer by remote control, like a human controlling a remote control model airplane. As discussed, though this distribution of functions was necessary from a "make it fit" perspective, the arrangement ultimately proved unfeasible for this design team to pursue.

Configuration Variant 2: The Glider

The second variant pursued by a Mini Team was a glider configuration. Inspired by designs shown to the team at Picatinny Arsenal, the concept called for a glider to be stored inside of the shell. The glider would then be ejected from the shell when deployed. Two methods of deployment were considered: pushing the glider out the nose of the shell or pulling it out from the back of the shell.

The first version pursued was pushing the glider out the nose. This concept constrained the design significantly however. The intent was to push the glider through the hole in nose now filled by the fuse. The diameter of this hole, however, is significantly smaller than the diameter of the rest of the shell. Since the glider was to be pushed through the hole, the hole's diameter limited the size of the fuselage. It turned out that under such constraints, the design would be nearly unfeasible.

The team then considered pulling the glider out the back of the shell. This arrangement would increase the diameter of the flyer significantly. The concept was given a further boost when it was discovered that the Army already possessed rounds of this nature in their inventory used to deploy illumination flares.

The glider's deployment sequence is shown in Figure F.3, and its general configuration is shown in Figure F.4.

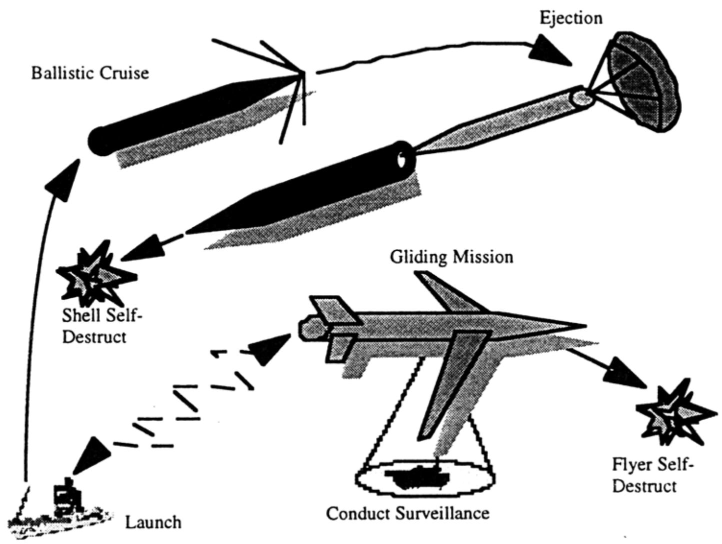

Figure F.3 Glider Deployment Sequence

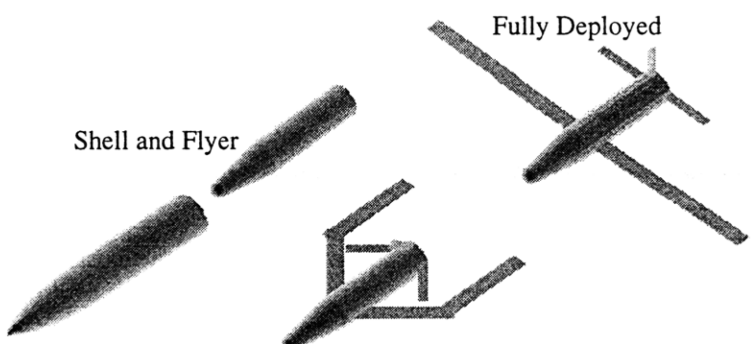

Figure F.4 Glider Configuration

Appendix G Test Vehicle Requirements

These requirements were developed by the design team to serve as guidelines during the design, development, and construction of the two test vehicles. It is expected that these requirements may change as the designs evolve.

The High-g Test Vehicle (HGTV)

Purpose

The purpose of the HGTV shall be to validate the structural design of the WASP vehicle. It does not, initially, need to demonstrate other functionality of the vehicle (computer systems, sensors, communications, etc.), but should accurately reflect the structural design and layout of the operational vehicle. This vehicle, should, however, be able to be modified to an operational configuration if components become available to facilitate such an upgrade.

Structure

As a vehicle intended for high-g tests, the HGTV must be able to withstand g-loads representative of those encountered by an operational WASP vehicle. All structures, therefore, must be designed to withstand these loads. Thus both the external shell of the vehicle as well as any and all internal support structures and surfaces (wings, tails, mounting points, etc.) must be designed to these loads.

In addition, for any component not included in the HGTV (see below), placeholder weights must be included. These weights should accurately represent the weight, density, and shapes of the components they are replacing.

Aerodynamic Configuration, Systems, and Deployment

Although intended for high-g testing only, the HGTV must incorporate any and all aerodynamic surfaces that will be used on the operational vehicle (wings, tail surfaces, propeller). These surfaces must be mounted as they would be on the operational vehicle. It is not required for flight control actuators to be included in the HGTV, but placeholder weights must be used.

Although the deployment system for the flight surfaces does not need to be incorporated into the HGTV, all surfaces must be able to be manually deployed to confirm functionality after high-g testing. If possible, every effort should be made to include the operational deployment systems on the HGTV.

Propulsion Systems

Since the propulsion system will be subjected to its own series of high-g tests, it does not need to be included in the HGTV. If the propulsion system has passed its high-g tests, however, every effort should be made to include the propulsion system in the HGTV. If the propulsion system is not included in the HGTV, placeholder weights must be used in its place.

Autonomy/Flight Control Systems

No computer systems related to autonomy aspects of WASP need to be included in the HGTV. Placeholder weights must be used to represent these components, however, and the vehicle should be capable of being modified to accommodate these systems in the future.

Communications

There is no need to include communications systems on the HGTV beyond systems used for data collection about the high-g tests. The HGTV should, however, be manufactured to allow for such systems to be incorporated at a later date.

Sensor Systems

No sensor systems need to be incorporated into the HGTV. Placeholder weights must be used, however, and the HGTV should be capable of being modified to accommodate sensor system components in the future.

Self-Destruct Mechanism

No self-destruct mechanism needs to be incorporated into the HGTV. Placeholder weights must be used, however, and the HGTV should be capable of being modified to accommodate the self-destruct mechanism in the future.

Ground Station

No ground station or related systems need to be developed for the HGTV.

The Air Drop Test Vehicle (ADTV)

Purpose

The purpose of the ADTV is to demonstrate the aerodynamic configuration of the operational WASP vehicle. Since validation of the aerodynamic configuration is the vehicle's primary mission, every effort must be made to ensure that the vehicle accurately represents the operational aerodynamic configuration of WASP. While the vehicle's structure should be designed for the high-g environment, its components need not be. In addition, while it is desired that the ADTV demonstrate some of the functionality of the operational system (autonomy, sensors, communications, etc.), such functionality can be sacrificed to achieve a configuration which exactly represents that of the operational vehicle. The vehicle should be capable of being modified to include the components needed to achieve full system functionality if they become available in the future.

Structure

The ADTV's internal structure and external shell should be designed to the high-g environment of the operational vehicle. In this regard, the ADTV and the HGTV should be identical. However, no internal components of the ADTV (electronics, engine, etc.), need to be capable of withstanding these loads. In addition, since the ADTV is to serve as an aerodynamic model of WASP, all components should be distributed to achieve the proper weight and balance of the operational vehicle. If needed, additional weights should be placed in the vehicle to achieve this distribution.

Aerodynamic Configuration, Systems, and Deployment

The ADTV must be an exact representation of the operational vehicle in terms of its aerodynamic configuration. In addition, all flight control surfaces must be operational, and the vehicle must demonstrate that it is controllable, either via on-board electronics or by remote control (see below).

The ADTV should also be capable of demonstrating the deployment of all flight control surfaces, as well as other deployable structures. The deployment mechanisms must be at least demonstrated in testing on the ground, and should also be demonstrated in flight (i.e., vehicle released in stowed configuration, then transforms into deployed configuration).

Propulsion Systems

The ADTV must have an operational propulsion system. This system should be an accurate reflection of the system that will be used on the operational WASP vehicle. The ADTV does not, however, need to demonstrate the complete loiter time or range of the operational vehicle if space that would be used for fuel is devoted to other equipment. If a complete fuel load is carried by the ADTV, however, it should be capable of demonstrating the operational mission performance.

Autonomy/Flight Control Systems

Systems related to vehicle autonomy and flight control must at least include those systems required to ensure that the vehicle is stable in flight (if such systems are required). Any additional systems related to vehicle autonomy can be included at the design team's discretion. The only restriction is that the vehicle must always conform to the operational vehicle's aerodynamic configuration. If the inclusion of autonomy-related systems would jeopardize this requirement, the systems will not be included. Any autonomy related systems that are included in the design, however, do not need to be g-hardened.

In the event that the vehicle can not accommodate autonomy related systems, the ADTV should be designed to operate as a remotely piloted vehicle. All components for such operation should then be included in the vehicle, and appropriate weights added to ensure that the vehicle still conforms to operational vehicle's weight distribution.

Communications

Any communications systems included in the ADTV should match the needs of the vehicle. In the event that the vehicle includes autonomy related systems, the communications system should be capable of relaying basic telemetry about the vehicle's state (position, attitude, altitude, velocity). If a sensor is included in the ADTV, the communications system should be capable to relaying imagery to the ground. In addition, if an operational ground station has been developed, the communications system should be capable of handling transmissions between the ADTV and the ground station.

Sensor Systems

A sensor should be included in the ADTV. The purpose of the inclusion of the sensor is to gain some data regarding image quality from an operational WASP vehicle. This sensor does not need to be g-hardened, but should allow for transmission of imagery to the ground.

Self-Destruct Mechanism

No self-destruct mechanism needs to be included in the ADTV. However, the vehicle should be capable of being modified to include such a mechanism in the future.

Ground Station

Every effort must be made to prepare some degree of functionality in a ground station for the ADTV. This functionality is dependent upon other factors in the ADTV design:

1. If the ADTV is remotely piloted, the ground station must incorporate the user controls to facilitate remote operation of the vehicle.
2. If a sensor is incorporated into the ADTV, the ground station must be capable of displaying images sent back from the flyer.
3. If autonomous systems are included in the ADTV, the ground station must do one of the following:
    - If two way communications are available, the ground station should be capable of sending commands to the ADTV's computer.
    - If two way communications are not available, ground station commands (i.e., a command stack) should be downloaded into the ADTV prior to its flight so that the vehicle can operate as though it was receiving a series of commands from the ground.

No matter what systems are eventually incorporated into the ADTV, the ground station must be capable of receiving and displaying any telemetry sent by the ADTV.

Note on ADTV/HGTV Commonality

Since both vehicles are to include structures that can withstand the high-g environment of the operational vehicle, the possibility does exist for the functions required of the two vehicles to be incorporated into a single vehicle. If such an option were to be pursued, a mechanism would have to be included in the design to facilitate the addition/removal of systems to be used in the drop tests but not the g-tests after/before such tests were conducted. It would be up to the discretion of the team to determine which vehicle configuration to construct first, depending on test plans.

Appendix H Task Flow Schedules

The following sheets contain the task flow schedules developed for the project. Note that a couple of weeks' schedules were not completed and are not included in this thesis.

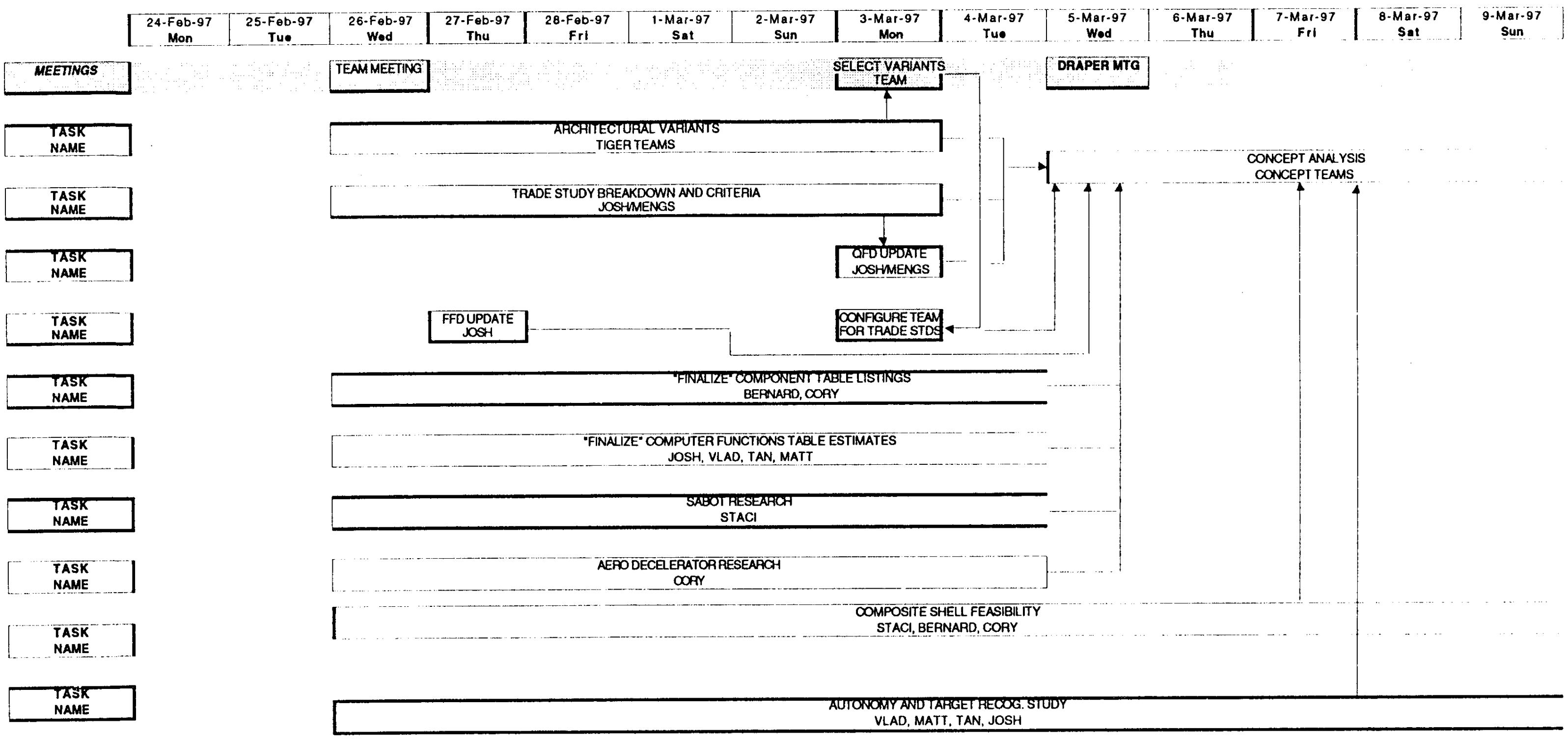

Figure H.1 Task Flow Schedule for February 24 to March 9

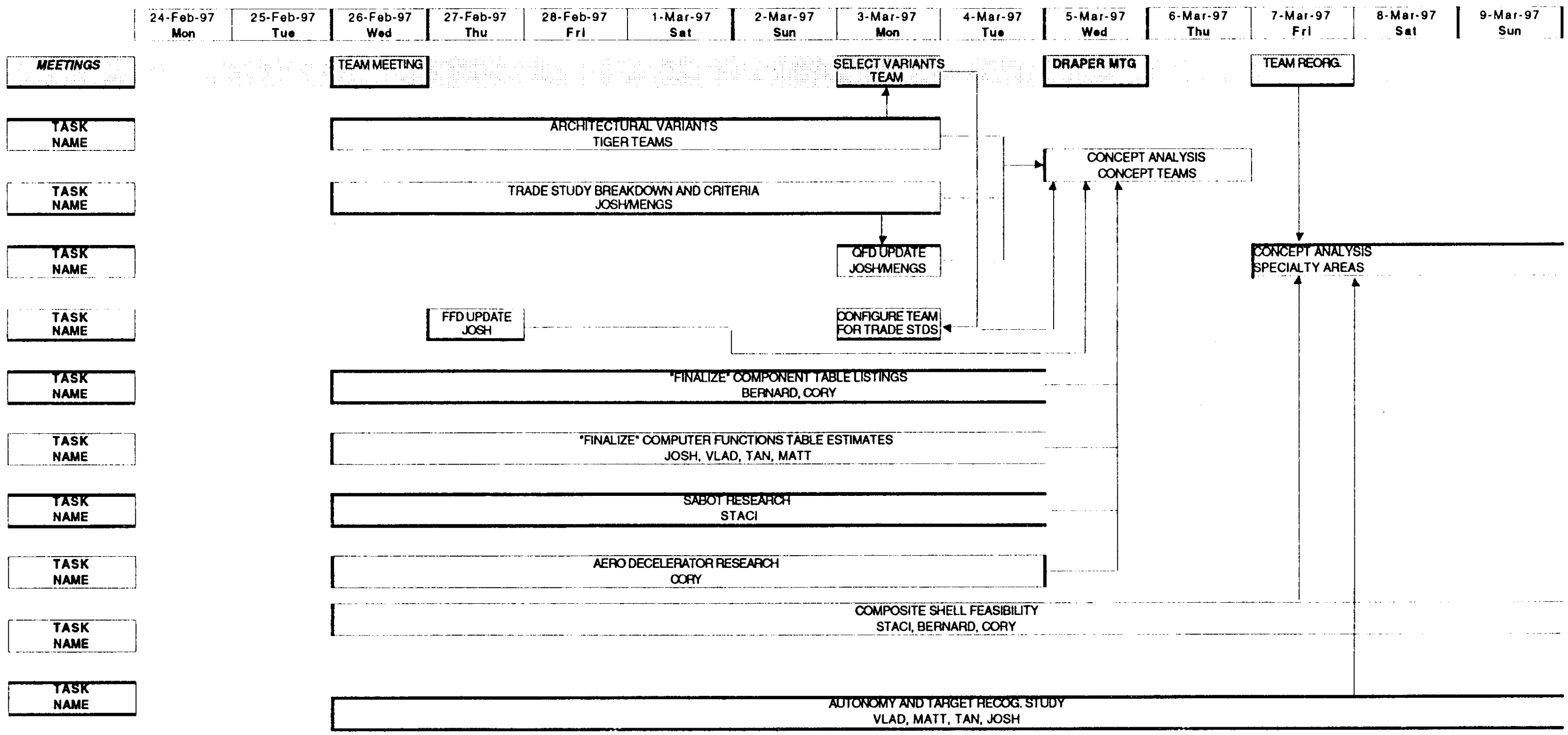

Figure H.2 Task Flow Schedule for March 10 to March 23

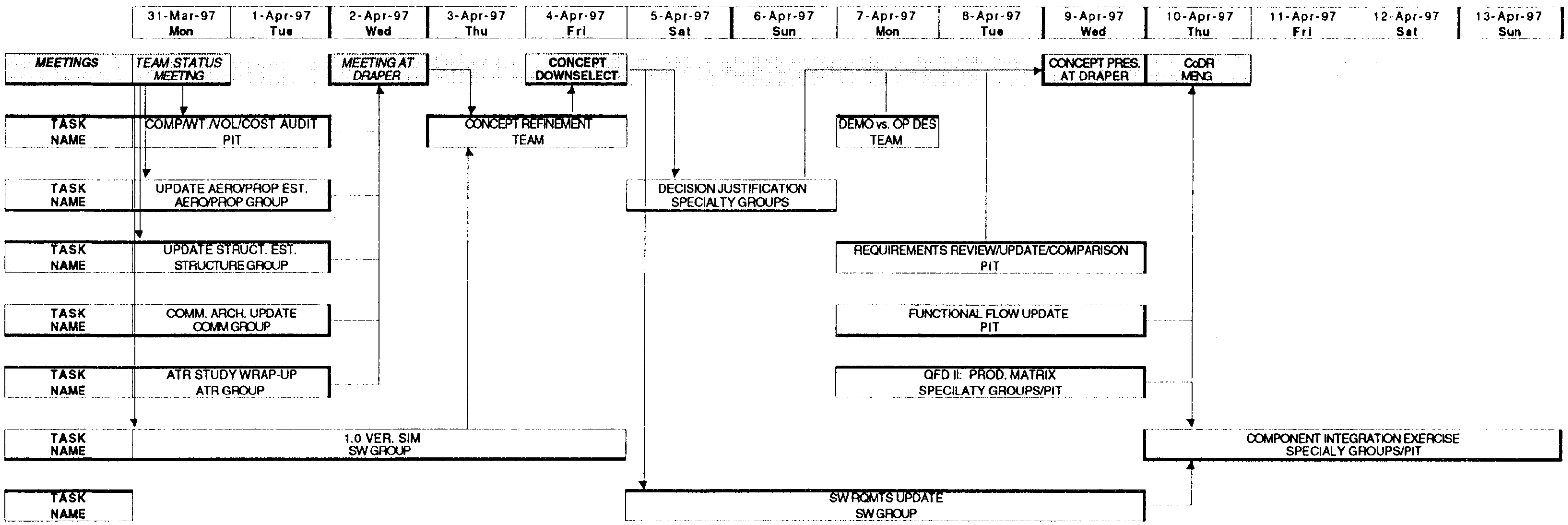

Figure H.3 Task Flow Schedule for March 31 to April 13

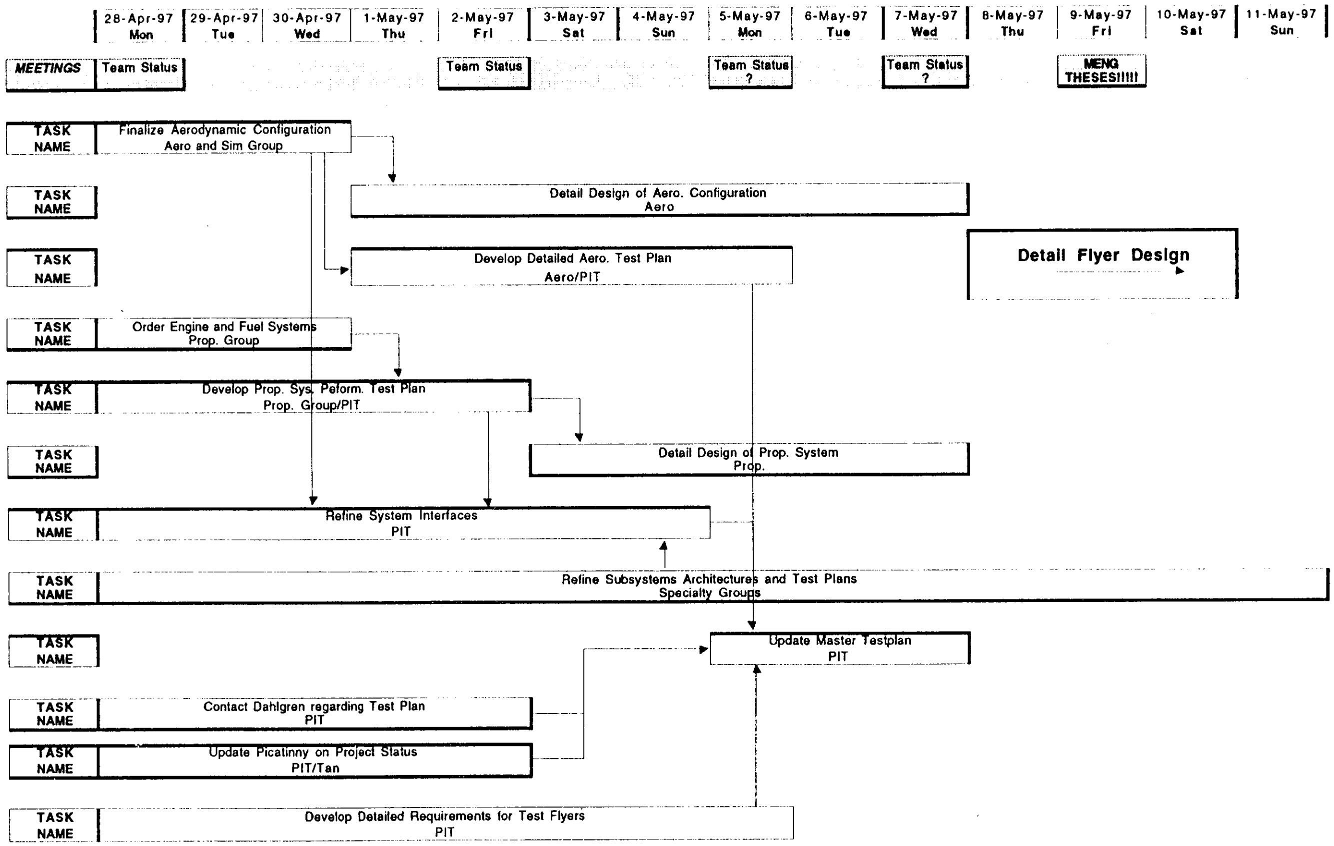

Figure H.4 Task Flow Schedule for April 28 to May 11