Concept Development, Mechanical Design, Manufacturing and Experimental Testing for a Cannon-Launched Reconnaissance Vehicle

by

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Abstract

The MIT/Draper Technology Development Project was conceived as a collaborative design and development program between MIT and the C.S. Draper Laboratory. The aims of the two year project were to develop a first-of-a-kind system and to stimulate entrepreneurship in the students working on the project. The first year saw the assessment of national needs and the selection of a project called the Wide Area Surveillance Projectile (WASP), a cannon-launched reconnaissance vehicle. The second year involved enhanced concept development, detailed design, manufacturing and testing of two prototypes: a high-g vehicle used to demonstrate the mechanical integrity of the design to survive a cannon launch and a flight test vehicle used to demonstrate its flying qualities.

This thesis covers the second year of the WASP project, focusing on concept development, mechanical design and experimental testing of the high-g prototype. This prototype was successful in its most recent test, demonstrating its structural integrity, with correct articulation of wing and tail structures, after launch from an eight inch gun in May 1998.

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CHAPTER 1

INTRODUCTION

1.1 Background on the MIT/DRAPER Partnership

In 1996, the Charles Stark Draper Laboratory approached the Massachusetts Institute of Technology to create a Technology Development Partnership. The goal of this partnership was to give graduate students the opportunity to design and develop a high technology product and to develop entrepreneurial skills. This Partnership was to identify and demonstrate a prototype of:

- An innovative, first-of-a-kind system
- A product that addresses national needs
- A high-risk project pushing the “unobtainium” limits
- An integrated, multi-disciplinary design process merging existing and future technologies
- A concept which is viable for both commercial and military applications
- A concept which is aligned with MIT and Draper Laboratory capabilities

In two years, a team of students, faculty and Draper engineers had to assess national needs, propose different project ideas, choose a potential project, and then design and manufacture a functional prototype.

The first year of work consisted primarily of assessing the market needs and developing a preliminary concept of the chosen project. The second year of work involved the detailed design, manufacturing, and testing of a prototype.

This thesis describes the work that has been done in the second part of the chosen project, from concept design to a working prototype.
1.2 Project Objective

Among five different project ideas reviewed in January 1997, the Wide Area Surveillance Projectile (WASP) concept was chosen. The goal of this project was to develop an autonomous rapid response surveillance flyer capable of sending real-time images to a ground station from distances up to 20 km away.

Conventional reconnaissance vehicles include satellites, high altitude airplanes, and large UAV's (Unmanned Autonomous Vehicle). Satellites are very effective surveillance tools, but they are not always available over a required area and the response time of high altitude airplanes and large UAV's can vary.

The WASP vehicle attempts to fill a new market segment. As shown in Figure 1.1, it is a shorter range reconnaissance vehicle with a radius of action. Primarily designed to suit Navy needs, the WASP is an inexpensive (less than $30,000 US dollars/unit) reconnaissance tool with very fast response capability. In less than two minutes from when a request is made, the WASP vehicle can begin supplying reconnaissance information, at distances of up to 20 km from its launch point.

![Diagram showing various reconnaissance systems and their characteristics]

**Figure 1.1: WASP Vehicle Market Niche**
In particular, the goal of the WASP design is to give an inexpensive and fast reconnaissance capability at a lower level of command. For example, the commander of a ship will be able to obtain local information without having to appeal to higher levels of command. A typical WASP mission scenario is shown in Figure 1.2.

Figure 1.2: Possible WASP Mission Scenario
Even though the initial design is tailored to suit military applications, the WASP product could be used in commercial applications as well. The most obvious is probably observation of forest fires but other forms of natural or man made disaster situations might also make use of such a system.

1.3 The Approach

1.3.1 Concept Demonstration

As mentioned previously, the WASP is a fast response reconnaissance vehicle mainly designed to be operationally flexible and inexpensive. It is to be shot from a five inch Navy gun and has to transform itself into a flying unmanned autonomous vehicle (UAV) capable of transmitting real-time images to a ground station. The main characteristics of the system are:

1. To be suitable for use with a five inch Navy gun.
2. To survive the forces of the gun environment.
3. To be able to loiter and be operational for a maximum amount of time.
4. To be autonomous.

The exact technical requirements will be detailed in the next chapter.

The two main challenges are: first to mechanically survive the gun launch and secondly, to be capable of autonomous flight. Eventually, the goal would be to produce a marketable product which the team calls the Operational Vehicle (OV).

Due to the compressed two year time frame of the project and unavailability of high-g qualified electronics, two separate vehicles (or individual prototypes) were designed and manufactured in parallel to demonstrate the capabilities of an eventual final Operational Vehicle as illustrated in Figure 1.3. In doing so, the two main challenges are separated, and concurrent developments can be achieved. The two vehicles are the High-G Vehicle and the Flight Test Vehicle.
1. The High-G Vehicle (HGV), will be used to demonstrate resistance to the launch environment and the system's mechanical integrity after launch. This vehicle will have no smart electronics on-board but mechanical systems should properly transform from the shell configuration into the flying vehicle after launch from a five inch Navy gun. The HGV can be seen as the Operational Vehicle first prototype. It provides space for the electronics but does not include the actual components.

2. The Flight Test Vehicle (FTV), will be an aerodynamically similar scaled up version of the HGV. Its goal is to demonstrate aerodynamic performance and flying qualities using standard off-the-shell electronics for a stability augmentation system. The FTV will also carry a camera and transmit real-time images to a ground station. The FTV will then serve as flying laboratory to adequately develop complete autonomous flight capabilities.

This separation of flight test program is necessary because no high-g electronics of sufficiently small volume are available to provide the necessary on-board system for the HGV. Draper Laboratory is currently developing those electronics but are still at experimental stage.
1.3.2 Planning and Scheduling

Appendix A is an overview of the project's planning and scheduling. This schedule covers the second year of work from August 1997 to end of May 1998. As both prototypes had to be ready and tested by May 1st 1998, the subsystem design deadlines and test dates were paced forward in time, taking into account as much as possible the team academic obligations. From July to September 1997, the team had to develop a viable concept design that could fulfill most of the project requirements. Detail component design started in September and was scheduled to last until December 1997. System integration and fabrication were scheduled for the last four months of the project from January to May 1998.

1.4 Team Organization, My Role and Thesis Overview

1.4.1 Team Organization

The WASP development team was composed of nine graduate and two undergraduate Aeronautics and Astronautics Engineering students. Among the nine Graduate students, six were MIT Graduates with Bachelors degrees in Aeronautics and Astronautics, two had Mechanical Engineering degrees from McGill University, Montreal, Canada and one had a Mathematics degree from Moscow University. I personally am from McGill University with a Mechanical Engineering Degree, Aeronautical Option. To help the team in project management, engineering and research, Professor John Deyst and Mr. Charlie Boppe, the team two main advisors, and professors Carlos Ceznik, Mark Drela and Mark Spearing were actively involved as well.

In the summer of 1997, I was invited by my two advisors to take over leadership of the project as the WASP Team Manager. My main role was to ensure that the whole team would successfully accomplish its primary task, which is to design and build the two working prototypes by May 1st 1998. I was mainly responsible for planning and scheduling, work breakdown, teammate responsibilities, work assignment and client contact (Draper Laboratory). The nature of this work lead me directly to play the role of a System Engineer and Mechanical Engineer as I oversaw prototype subsystem's integration and some mechanical design.
The WASP is composed of two main elements: a modified 5 inch Navy shell and a flying vehicle that is inserted into this shell (detailed in the next chapters). The whole WASP design is configured to be as modular as possible. Individual team responsibilities were derived from the nature of these physical design modules. Figure 1.4 shows the team organization in terms of the design groups.

![Figure 1.4: Organizational Chart](image)

Each Group is defined as follows:

1. Wing Group: this group is responsible for the entire wing design and determines the stability characteristics and aerodynamic efficiency for different flyer configurations.

2. Propulsion Group: this group is responsible for the propulsion system choice and design, propeller design, power output, fuel consumption estimation, and engine start-up system design.

3. Shell and Ballistic Group: this group is responsible for the modification / design of the five inch Navy shell, its stability in ballistic flight and the separation sequence as the flyer exits the shell.

4. Ground Station, Electronics and Hardware / Software Group: this group is responsible for the control and guidance electronics and the control algorithms of the flyer, the ground station development and RF communications. This work was directly applied on the FTV.
5. Internal Structure Group: this group is responsible for the configuration management of all sub-systems including propulsion, wings, tails, servos and electronics and is responsible for the design of the high-g resistant internal structure and the deployable control effectors including all gearing systems.

6. Simulation group: this group is responsible for deployment sequence of the entire WASP, its reliability analysis, separation simulation and separation state stability analysis.

Each team is responsible for its own experimental component testing. It is also important to point out that people are not limited to their own work and they often participate in the details of a design within another group.

1.4.2 My Role Within the Organization and Thesis Overview

From a technical design point of view, I am responsible for the Internal Structure group. My thesis will cover the development of the high-g internal structure and tail deployment mechanisms of the flyer, from concept design to manufacturing of the actual working high-g prototype. The internal structure can be considered as one of the physical links between all WASP subsystems.
CHAPTER 2

CONCEPT DEVELOPMENT

2.1 Design Requirements

2.1.1 Original Requirements

Based on the work of the 1997 team, the main customer requirements(1) defined by the team and Draper Laboratory were:

Customer Requirements

1. Long Loiter
2. Long Operational Time
3. Low Cost
4. Ease of Operation
5. Very Safe
6. Accurate Image Position Determination
7. Near Real-Time Information Processing
8. Ease of Maniability
9. Maximum Field of View
10. Maximum Image Resolution
11. High Degree of Autonomy
12. High Reliability
13. Long Range
14. Strong Stealth Characteristics
15. High Extensibility
16. Minimum Self Destruct Debris
17. Long Shelf Life (storable)

Table 1: Original Customer Requirements

The requirements characterize attributes for the system that the team had to try to deliver. Many of these relate to different requirement categories and it was difficult to appreciate at first the main design challenges. As more and more information on these requirements was gathered by the team, the requirements were re-evaluated and the most important ones were identified.
2.1.2 Re-Evaluation of the Requirements

Functionality took precedence over performance and a lot of requirements such as Long Loiter, Long Range and the ones related to the filming performance had to be re-evaluated. The team screened the requirements capturing what really was the challenge in designing and building the WASP. The following requirements are the ones along which the WASP prototype system was designed and developed.

New Customer Requirements

1. The design has to survive a five inch gun launch and environment
2. Standard five inch gun round dimensions have to be met (e.g. MK 64 shell) to enable easy auto-loading, single ram and easy shelf storage
3. The product should be storable and inexpensive (less than $30,000) for production units
4. The reconnaissance vehicle should be autonomous
5. A ground station has to be developed to receive real-time data and images
6. The design should maximize the flying vehicle loiter time
7. A good ballistic range is desired

Table 2: New Customer Requirements

2.2 The Challenges

This section is intended to give an overview of the technical challenges the team was faced with. Each challenge will directly influence the prototype concept detailed development.

2.2.1 Understanding the Gun Environment

2.2.1.1 The Gun and the Shell

Figure 2.1 is a typical Navy gun schematic. A shell is first inserted through the Breech Recess and is pushed against the Forcing Cone of the Barrel. The appropriate amount of powder is then inserted behind the shell in the Powder Chamber. The whole assembly, projectile plus charge, is squeezed by the Breechlock when closed. In doing so, the front part of the projectile is forced in
2.2.1.2 The Forces

When a shell is launched from a five inch Navy gun using regular charge, the main forces are:

a) *The set-back acceleration*: the pressure generated from the ignited powder pushes on the aft end of the shell and on the obturator band to accelerate the whole system at about 12,000 g's. The duration of the pressure wave lasts for 20 milliseconds. The set-back acceleration is directly linked to the shell overall weight and for a standard charge, the bigger the mass, the smaller the acceleration is and vice-versa. Using a standard charge, a five inch shell has an optimum weight of 70 lb (optimum equilibrium between projectile launch momentum and drag force).

![Range vs. Launch Weight](image1)
![Peak Acceleration vs. Launch Weight](image2)

**Figure 2.3: Effect of Weight on Range and G Loading**

b) *The set-forward acceleration*: as shown in Figure 2.4, the shock wave of the blast propagates in the shell material and bounces back after reaching the nose of the shell. The whole shell assembly can be considered as a spring/damper system with individual internal elements. Based on experience, a 4,000 g linear deceleration can be anticipated once the projectile exits the barrel and compression energy is released. This phenomena is also called rebound.
the so called Forcing Cone aligning it properly with the Barrel Main Bore. In Navy guns, the barrels are rifled to impart a right hand spin to the projectile for a spin stabilized ballistic flight.

![Diagram of a Typical Navy Gun](image)

**Figure 2.1: A Typical Navy Gun**

Figure 2.2 is a schematic of a typical five inch Navy shell highlighting its main characteristics. A shell is composed of a main body in which a primer and the main charge are inserted. The nose of the shell is closed by a Fuse that controls the ignition of the charge. On the main body of the shell, the Obturator is normally a copper, sintered iron, nylon or plastic ring that seals the hot and high pressure gases behind the shell when the gun powder is ignited. The obturator has an interference fit with the barrel internal diameter and is responsible for the spin of the projectile as it is grooved by the barrel rifling. The aft end of the shell has normally a “boat tail” shape that reduces aerodynamic drag in ballistic flight.

![Diagram of a Typical Five Inch Navy Shell](image)

**Figure 2.2: A Typical Five Inch Navy Shell**
c) **Balloting:** forward segments of the projectile body that do not fit tightly in the barrel, effectively bounce off the barrel sides as the projectile is accelerated forward down the barrel. A 1,000 g lateral acceleration can be experienced due to balloting.

d) **Angular acceleration:** the rifling in the gun imparts the spin motion to the shell causing angular accelerations and associated torques. When exiting the barrel, the spin of the shell is between 200 and 250 hz, depending on the caliber of the gun and the type of rifling.

e) **Other forces and constraints:** the shell is submitted to additional forces such as the high gas pressure (around 65Ksi), friction and heat. With a regular charge, the exit velocity for an optimum 70 lb shell is approximately 2245 ft./s or 680 m/s. To help understand the set-back and set-forward forces, Figure 2.4 chronologically illustrates the firing sequence.

1. **Pressure Force**
   - The charge develops 65 ksi of pressure

2. **Instantaneous Stresses Induced**
   - Stress waves are induced with much greater magnitude than quasi static stresses. Strain rate effects are important.

3. **Acceleration**
   - Stress waves cause global acceleration of the projectile.

4. **Compressive Deformation**
   - Stress, strain and displacements are induced by inertial forces. Buckling is important in this regime.
5. Compression due to Wall
- At the obturator, the shell cannot deform greater than the diameter of the barrel of the gun. Therefore, a lateral pressure is induced in the projectile wall to ensure displacement compatibility.

6. Vibration or “Rebound”
- Because the inertial force is not applied slowly, the projectile undergoes a dynamic response. The projectile vibrates. Vibration of the internal components is a concern in this regime.

7. The Projectile Leaves the Barrel
- Vibration occurs after the projectile leaves the barrel until material and acoustic damping cause displacements to decay to zero. Then lift and drag are the only force acting on the projectile.

Figure 2.4: Firing Sequence Decomposition

2.2.2 Understanding Ballistic Flight

All Navy guns impart spin to their projectiles. The angular momentum helps to keep the projectile aligned with its trajectory even though the shell Center-of-Pressure (Cp) is located in front of the shell Center-of-Gravity (Cg). The shell is said to be spin stabilized (see Figure 2.5).

Another way to assure a stable ballistic flight in the absence of rotation, would be to add fins on the aft end of the shell so as to move the Cp behind the Cg. However, adding fins would increase drag and reduce the range of the shell\(^{(2)}\).
As mentioned previously, standard five inch Navy Mk 64 shells have "boat tail" aft ends. A 6.5 degree boat tail reduces wave and base drag and helps increase the range by 30% with respect to a "blunt tail" aft end. This design characteristic could influence the team's shell selection decision.

2.2.3 Understanding Aircraft Flight

The flying vehicle will be required to survey an area and loiter for a maximum amount of time. Hence, the aerodynamic performance characteristics of the flyer are important and they are closely related to:

- Weight.
- Cg location and excursion.
- Inertias.
- Size and location of flying and control surfaces.
- Aerodynamic shape of the main body of the vehicle.
- Propulsion (if any) power and efficiency.
- Control capacity of on-board electronics, especially if the airframe is statically or dynamically unstable.
As a general rule, the lighter the vehicle is, the slower it can fly, and the smaller the propulsion power can be for level flight. Also, the further forward the Cg is from the aerodynamic center (Ac), the larger the static margin and the more stable and less responsive the vehicle is in the longitudinal plane. Many other rules apply, but these are very useful for concept design.

2.2.3 On-Board Equipment

For an autonomous flight and a filming mission, some key on-board equipment is required. A Draper high-g computer, GPS and full inertial system are the attitude and position control heart of the flyer. A transmitter and a receiver are used to communicate with the ground station and send back mission data such as flyer, position and pictures from the on-board camera. Actuators are required to activate all flyer control surfaces and batteries are necessary to power the entire system for a sufficient amount of time. A list of the necessary on-board equipment including individual component volumes and dimensions is shown in Appendix B1. The Signal Flow diagram of the Operational Vehicle\textsuperscript{(3)} is shown in Appendix B2.

The WASP design has to provide space for this equipment and a careful layout of all the components is necessary to optimize space use, Cg location and minimize overall system complexity.
2.3 Concept Brainstorming

2.3.1 Brainstorming on Challenges

The first year team had the chance to explore many different concepts. Data on gun environment, ballistics, and other projects was gathered and some preliminary wing / tail configurations were looked at. However, the concepts developed by the first year team, were at a high level and there was a need for more detailed concept design.

Early in the second year of effort, each team worked to explore design ideas and limitations in their area of responsibility. Ranges, dimensions and volumes of each subsystem design were determined. The wing design team looked at different alternatives, each one requiring different internal structure volume. The propulsion team worked with preliminary drag estimations to obtain propulsion unit volume estimation sizing different engines, fuel tank or battery size for eventual electric propulsion.

The different teams were all working and brainstorming concurrently to elaborate different viable concepts that could meet the following technical requirements.

<table>
<thead>
<tr>
<th>Technical Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Acceleration</td>
</tr>
<tr>
<td>2. Flyer Weight</td>
</tr>
<tr>
<td>3. Ballistic Weight</td>
</tr>
<tr>
<td>4. Internal Structure</td>
</tr>
<tr>
<td>5. External Dimensions</td>
</tr>
<tr>
<td>6. Loiter time</td>
</tr>
</tbody>
</table>

Table 3: Technical Requirements
Some requirements are contradictory. For example, on one hand the flyer has to be as light as possible for good aerodynamic performance and on the other hand, the entire design has to aim for a target optimum launch weight of 70 lb.

2.3.2 Gathering and Evaluating Ideas

Along with the internal structure, propulsion, electronics and wing / tail requirements, the team was faced with a number of other important challenges:

These are what might be called the “How” Questions:

*Technical How Questions:*

1. How to actually transform the projectile (that will have to survive the gun environment and acceleration) into a efficient reconnaissance flyer?
2. How to slow the projectile down from the ballistic supersonic flight speed to an operational flying velocity?
3. How will the spin imparted by the gun barrel rifling going to affect the design and if no spin is required when transforming the projectile, how can it be eliminated?

*Project Management How Questions:*

4. How compatible is the design with normal Navy shell characteristics (marketable issue)?
5. How risky and complex can the WASP design be, considering that the team has less than one year to produce a working prototype (project deadline issue)?

After considerable deliberations, four main ones were retained from a large collection of earlier concepts. These are:

- Concept I: The Sabot-Enclosed Flyer
- Concept II: The Composite / Metal Flyer
- Concept III: The Shell-Contained Flyer
- Concept IV: The All Metal Flyer
For each of them, a list a positive and negative attributes are associated. In total, eight main weighted attributes are used to characterize the concepts. They are listed below in Table 4.

<table>
<thead>
<tr>
<th>ATTRIBUTES</th>
<th>WEIGHT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Design Simplicity</td>
<td>8</td>
</tr>
<tr>
<td>2 Manufacturing Simplicity</td>
<td>8</td>
</tr>
<tr>
<td>3 No De-Spin Necessary</td>
<td>7</td>
</tr>
<tr>
<td>4 Protected From Launch Environment</td>
<td>7</td>
</tr>
<tr>
<td>5 Large Internal Volume</td>
<td>6</td>
</tr>
<tr>
<td>6 Long Range</td>
<td>7</td>
</tr>
<tr>
<td>7 Good Loiter performance</td>
<td>7</td>
</tr>
<tr>
<td>8 Auto-Loading Possible</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 4: Concept Attributes

Description of the attributes:

1. *Design Simplicity*: the deployment mechanisms are simple, the design has few parts
2. *Manufacturing Simplicity*: most of the parts are metal, the design only requires conventional machining.
3. *No De-Spin Necessary*: the design uses a sabot or a slip ring obturator that prevents the projectile from spinning. A non-spinning projectile simplifies the transformation process from projectile to flying vehicle.
4. *Protected From Launch Environment*: a metal shield such as the shell itself protects and isolates the flyer from the hot gases and high pressures at launch.
5. *Large Internal Volume*: a large internal volume offers more space in which to fit all required internal components.
6. *Long range*: a significant launch mass is required to obtain long range characteristics.
7. *Good Loiter Time*: the lighter the flyer is, the better the loiter time should be.
8. *Auto-Loading Possible*: the external shape of the projectile should be compatible with standard auto-loading systems of Navy guns.
CONCEPT I: The Sabot-Enclosed Flyer

Concept I, shown in Figure 2.6, would have a light flyer bouy, less than five inches in diameter, and enclosed by a sabot. The first role of the sabot is to adapt the diameter of the flyer to the gun barrel. The sabot would have a five inch external diameter to meet the five inch gun compatibility requirement. Playing the role of an obturator by retaining the gases behind the launched body, the polymer sabot will also impart a low spin rate (5 to 10 hz) as its internal surface would slip on the flyer body. The sabot would tear apart, due to centrifugal and aerodynamic forces as soon as the whole projectile exits the barrel.

![Diagram of Concept I, Sabot Enclosed Flyer]

Figure 2.6: Concept I, Sabot Enclosed Flyer

The projectile would be fin stabilized until it transforms into a flying autonomous vehicle. A special parachute would slow whole system down before deploying the wings and control surfaces. For this concept:

The positive attributes are:

1. Protected from gun barrel as there is no contact between the flyer itself and the gun barrel.
2. De-spin is not necessary as the sabot will limit the spin rate at launch.
3. Using an off-the-shelf tank round sabot, it will reduce the complexity of the design.
4. The flyer is light, a good loiter performance is expected.
The negative attributes are:

1. A light projectile has a reduced range and higher launch g’s.
2. Auto loading is not possible using a tank round sabot configuration.
3. The concept does not offer a large internal volume.

CONCEPT II: The Composite / Metal Flyer

Concept II, as shown in Figure 2.7, will have long ballistic range and good loiter performance because metal protective enclosures are discarded when the projectile to flyer transformation occurs. The main body of the aircraft could be built out of composites, strong and stiff enough for a cannon launch and light enough for good loiter time. The additional metal enclosures would add launch mass and also protect the flyer body from the barrel rifling and hot gases as the obturator would be mounted on the aft metal section. A special parachute is also required, as in Concept I, to slow projectile before deployment.

![Diagram of Concept II: Composite / Metal Flyer]

**Figure 2.7: Concept II, Composite / Metal Flyer**

This interesting concept has the following characteristics:
The positives attributes are:

1. The concept offers long range because the optimum ballistic weight could be achieved by adding the metal protective enclosures.
2. The airframe of the flyer is partially protected from the gun barrel.
3. The concept offers a large internal volume because its diameter is almost the size of a standard MK 64 five inch round.
4. Autoloading is a likely possibility.

The negative attributes are:

1. Composite materials add a lot of manufacturing complexity, design complexity and risk.
2. The design may be fragile because a scratch or a crack on the composite body could significantly weaken the composite matrix.
3. De-Spin would be needed if a standard obturator band is used.

CONCEPT III: The Shell-Contained Flyer

Concept III is an extended version of Concept II as the whole flyer is enclosed in a protective metal enclosure. This concept, shown in Figure 2.8, offers long range as the optimum ballistic weight can be meet. Good loiter performance can be achieved as the metal protective enclosures are discarded at transformation. This concept is fin stabilized and a slip ring obturator band limits the spin of the whole projectile at launch (5 to 10 hz instead of 250 hz). The outside shell would separate in two and a parachute would decrease the velocity of the internal flyer only. As in the previous concepts, all necessary control effectors and wings would deploy to start the planned mission.
The characteristics of this concept are:

*The positive attributes:*

1. Optimum ballistic weight offers a long ballistic range.
2. The internal flyer is fully protected from launch environment and barrel surface.
3. Auto-loading is possible.
4. Using a slip ring obturator, no de-spin would be necessary.
5. This concept would have a reasonable internal volume.
6. The protective external shell and the flyer could be two independent items only linked by the internal geometry of the shell and the loads the flyer and shell would see.

*The negative attributes are:*

1. The transformation issue could be complex.
2. Some features such as the conformal fins could be additional design challenges.
CONCEPT IV: The All Metal Flyer

Concept IV is a metal flyer concept where the main body serves as a shell and as a fuselage. No separation is required and when wanted, wings, tail, propeller can all deploy freely from the main body to create a flyer. A parachute will also be needed to slow down the whole system to an appropriate deployment and reconnaissance flight speed.

![Diagram of Concept IV](image)

**Figure 2.9: Concept IV, The All Metal Flyer**

The main characteristics of this concept are:

*The positive attributes are:*

1. This concept offers long range as the optimum ballistic weight can be matched.
2. Less parts are involved and no "separation" is required so design simplicity and manufacturability are better than previous listed concepts.
3. This concept offers the largest internal volume of all.
4. All flyer systems completely protected from the launch environment.

*The negative attributes are:*

1. The flyer is very heavy and will not have much loiter time.
2. De-spin is necessary if the projectile is spin stabilized.
CONCEPTS results:

The following table summarizes the design attribute scores of the individual concepts:

<table>
<thead>
<tr>
<th>Concepts</th>
<th>Positive</th>
<th>Negative</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>29</td>
<td>13</td>
</tr>
<tr>
<td>II</td>
<td>24</td>
<td>18</td>
</tr>
<tr>
<td>III</td>
<td>31</td>
<td>16</td>
</tr>
<tr>
<td>IV</td>
<td>28</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 5: Concept Results

Concept I and III were the two winners. The final choice between them was not clear and the team needed more information to appropriately decide which concept to adopt.

2.3.3 Layout and Balance

Along with the development of the different concepts, many component layouts were sketched and designed in order to determine the most efficient use of the available internal volume. Different wing and tail positions were tried, necessary fuel tank, batteries and electronics were moved around for the different concepts and overall Cg location was estimated for individual designs.

Also, the wing group was investigating different concepts such as telescopic wings, inflatable wings and folding wings. Each of these concepts required different volumes as the wings and the control effectors had to be folded and stored within a five inch diameter internal structure\(^4\), or smaller.

Preliminary flyer stability analyses were performed for different wing and tail configurations and geometries. The propulsion unit group studied various engines and fuel tank sizes for differ-
ent drag estimates. Also, a list of components and their sizes, weights and performance characteristics was developed and refined every month as more information was gathered.

Four scaled down hand sketch layouts for concepts I, II and III can be found in Appendix C. The contour size and geometry is the one from the MK 64 Navy shell and the goal was to fit all required components within that volume. Estimated Cg location is drawn and overall weight is calculated. On some of the sketches, one can also observe electronic wire connections to group the systems efficiently minimizing wire length and system complexity.

2.4 Concept Choice

During this concept iterative process, more information regarding guns, their environment, related R&D projects was gathered. Much time was invested in searching for ideas and viable designs that would help to solve the challenges. Fin minimum surface areas were determined for a stable ballistic flight based on estimated Cg location. Preliminary FEM (Finite Element Method) stress analysis was done to determine the viability of certain geometries and interactions between the internal flyer and the metal enclosures or the shell in Concept I and III. The goal was to answer the various “How” questions.

One of the major “How” questions was:

“How to transform the ballistic projectile into an efficient reconnaissance flyer?”

First, the “sandwich theory” was investigated. Shown in Layout Concept III in Appendix C, two metal half shells would be bolted together using explosive bolts. At transformation in the ballistic flight, the two halves would separate freeing the internal flyer and a parachute.

In the course of these investigations, the team became aware of Navy illuminating rounds. Figure 2.10 shows the illuminating round, or Mk 48 MOD 1 Navy shell. This shell is a five inch projectile that has dimensions quite similar to the MK 64 round and it is used to “illuminate”
areas. An illuminating unit combined with a large parachute are jettisoned from the back of the shell by a pyrotechnic charge at a desired altitude over an area of interest.

Figure 2.10: The Illuminating Round MK 48 MOD 1

The whole assembly is shot from a five inch gun, and hence sees the same 12,000 g's set-back and 4,000 g's set-forward accelerations as the MK 64. This projectile has been proven in operational use and has a reliability of 75%.

After many debates, the team chose to investigate the illuminating round as a container for the flyer. By extracting the flyer from the main shell, the design flyer would be rid of the excess ballistic mass, thus achieving good loiter performance. Also, the entire flyer would be protected from the extreme launch environment by the shell. The separation or the "how to separate" question was not yet answered but at this point, the main concept was determined, and each individual mini-team could design this top-level architecture.
CHAPTER 3

FIRST INTERNAL STRUCTURE DESIGN

3.1 Design Considerations

As described in Chapter 2, trade studies resulted in the selection of Concept III implemented with a standard Navy illuminating round projectile body. At this point, each team took on the task of designing and developing in detail the various subsystems. Since the author's responsibility is the internal structure, the content of this thesis describes the development of the flyer internal structure. The structure can be thought of as the backbone of the flyer and its geometry, shape and weight are directly affected by all other subsystems.

3.1.1 In Hand for the First Internal Structure Design

Preliminary aerodynamic performance and configuration studies were done\(^{(4)(5)}\) in the concept design phase. The flyer needed two horizontally shifted folding wings and two tails inclined at 35 deg. from the horizontal to control pitch, yaw and roll aircraft motions. Figure 3.1 is an aerodynamic model schematic of the flyer configuration.

![Figure 3.1: Schematic Configuration of the WASP Flyer](image-url)
Blueprints for the MK 64 five inch Navy round were also available from the Navy (see Appendix D1) and could be used to size and estimate the available internal volume that the flyer could safely occupy. No MK 48 detail drawings were received but the similarity between the two shells was sufficient to start a design.

Shown in appendix B1 is a list of all required components and Draper Advanced Technology Demonstration (ATD) electronics and their respective dimensions. Three accelerometers and three gyroscopes mounted in the X, Y, Z axis (Roll, Pitch, Yaw) constitute the Inertial Measurement Unit (IMU) for the flyer.

A trade study(6) indicated that the propulsion unit should be a two-stroke internal combustion engine, combined with a custom designed propeller. Due to structural reasons, the propulsion unit would be located in the nose of the flyer. The propulsion unit is a “Puller” instead of a “Pusher” (engine located in the aft end of the flyer).

At this point, the main design considerations for the internal structure were:

1. Shell geometry and allowable internal volume
2. Set-back and set-forward acceleration
3. Mass of the internal structure
4. Mass of individual subsystems that will fit into the internal structure
5. Dimensions of all subsystems that will fit in the internal structure including gas tank, batteries, electronics and hardware equipment such as the propulsion unit, the wings, the servos, the tails.
6. Cg location
7. Positions of the wings and the control effectors and their respective dimension
8. Positions of closely related subsystems to reduce complexity
9. Overall flyer ease of assembly and manufacturing
10. Simplicity of the overall system
3.1.2 CAD package

The team was equipped with Pro-Engineer CAD software running on a Silicon Graphic Station. Pro-E proved to be very useful as three dimensional visualization and solid modeling are the core of the program. Also, its compatibility with COSMOS and ANSYS Stress Analysis software packages greatly accelerated the design process. Pro-E could transfer IGES files that were used on MasterCAM for complex 3D machining.

3.2 Modular Concept

3.2.1 First Design Goals

The first design goal is to create a realistic vision of the flyer internal structure. It is very difficult to address all constraints simultaneously so the main objective is to create a vision based only on:

1. The shell internal geometry (a cylinder).
2. The fact that the internal structure must interface with the wings, tails, various electronics, a propulsion unit and a camera.
3. Some concept preliminary stress analysis and research on how to build a structure that can survive 12,000 g’s of acceleration and 4,000 g’s rebound.
4. The design simplicity criteria.
5. The preliminary concept design (location and preliminary size and shape of mechanical components as determined by the aerodynamic simulations).

3.2.2 Modular Vision

As described above, a primary goal was to create a vision that highlights the design simplicity criteria. One way to do this is to partition the entire internal structure into individual modules. Each module would carry a main mechanical component consistent with assembly requirements. The flyer was separated into three primary modules.
1. **The Tail Module:** contains the two 35 deg. anhedral tails (or control effectors), two appropriate servo-motors, the gearing system for their articulation and most electronics.

2. **The Wing Module:** supports the folding wings, some electronics and the fuel tank.

3. **The Propulsion Module:** supports the entire propulsion unit, its starting mechanism, propulsion controls and the folding propeller.

Dividing the internal structure into different modules had the effect of isolating the subsystems and limiting the complexity of the interfaces between them. As it can be seen in the “Internal Structure Vision Sketch” in Appendix E1, each module is itself divided into modules. The wing system or “Wing Box” is inserted into the Wing Module as a module in itself. The contact and all interactions between the wing system and the Wing Module are then limited. In doing so, the foldable wing system for example, becomes independent and is only constrained by the dimension of the space in the Wing Module. Any type of foldable wing system could be developed independently as long as it is compatible with the Wing Module interface. Also, using a modular concept, it is easier to isolate a potential design errors and to redesign the subsystem so as not to affect the rest of the system.

**Solid versus Space Frame Structure and Module Number Limitation**

The “Vision Sketch” in Appendix E did not yet represent the three distinct modules. However, the sketch illustrates a way to mount all required electronics in the internal structure. In a high-g environment, the goal is to eliminate any possible empty spaces. Displacement is NOT ALLOWED as all components are accelerated with 12,000 g’s forward and 4,000 g’s backward 20 ms later as the projectile feels rebound at the exit of the barrel. Therefore, the goal is to imbed all electronics in the modules by digging cavities and filling the extra electronics-cavity space with a Glass Bead Wax technique previously used and proven at Draper Laboratory. This wax behaves like an incompressible fluid under high g’s. Thus, for first design simplicity reasons, a decision was made not to look into a space frame structure as it would complicate the design trying to stick with the “No Displacement” criteria.
Even though it is important to separate the internal structure into separate modules, caution must be taken not to divide it too much. When the powder of the gun detonates, the blast acts like a hammer on the projectile body aft end. The pulse propagates through the material exiting every single components. The whole structure behaves like a spring-mass-damper system oscillating back and forth in many different modes. If two adjacent modules are not in phase, it could compromise the interface. The more modules there are, the more interfaces there will be, and the more complex the design will become.

3.3 Internal Structure Design

Starting from the preferred concept system architecture, the first goal was to design the internal structure to fit all required mechanical components and electronics. Based on the Internal Structure Vision Sketch, the first design was used to determine the main dimensions of the flyer, from module length and diameter to overall length.

Since the flyer is contained within a five inch Navy shell, the length and diameter limitations are essentially determined by the allowable internal volume of the shell. The 5 inch MK 48 projectile has an internal diameter of 3.9 inches and about one foot in internal usable length (350 mm). The front part of the shell tapers and requires the same from the flyer in that region. When the fuse is screwed on, the overall length of the projectile is 26 inches.

3.3.1 The Tail Module

Following the Illumination round concept, the entire flyer will be pulled out of the shell by the base. It was agreed that the flyer would be inserted nose forward in the shell so that at separation, the flyer would be facing the flow. Therefore, the Tail Module should be the last module of the flyer and hence will have to carry its own inertia plus the load of the two other modules on top of it at launch. The following is the list of the components contained in the Tail Module:
Tail Module Components

1. CPU
2. Ethernet
3. GPS
4. Transmitter / Receiver
5. Camera
6. Servo-Motors
7. Adequate gearing system
8. Two tails or control effectors
9. Three accelerometers
10. Three Micromechanical Gyros

Table 6: Tail Module Components

Geometry Consideration:

The two tails of minimum required length of 11 cm for a chord of 4.5 cm, determine the length of the module. They are stored at 35 deg. from the horizontal and can rotate about a pivot situated at the aft end of the module to gain as much tail length as possible. The tails should be spring loaded and retained by the outside shell until the flyer is extracted at separation. Around those two pivoting surfaces are arranged all required electronics. On the inner surface of the module, the top square box fits the CPU, the transmitter / receiver, the GPS unit and the Ethernet card. The two vertical cuts are used to store one accelerometer and one gyroscope. Below the tails fit the remaining accelerometer and gyroscope. The camera is approximated by a 6 by 2 by 4 cm cut in the bottom face of the module. To date, only one high-g camera is available on the market (developed by Xybion) but its dimensions are too large for the WASP design. The camera size approximation is hence based on a known small non-high-g camera, hoping that soon a high-g version will become available.

The tails need to rotate about two different axes. The first one allowing deployment and the second one allowing servo motors incidence angle control. This first design allows an easy assembly of the tail mechanism and provides an idea how to connect the yet unknown dimensioned servo-motors to the tail pivots. The design of the control effectors will be detailed in Chapter 4.
The inner face of the Tail Module is sealed by a seal plate, enclosing an electronic backplane board connecting all the cards together (the connection pins of the Draper CPU and Micromechanical gyros and accelerometers exit sideways and can therefore be easily connected). The electronic interface with the Wing Module is done through one connection that passes through the seal plate. Finally, one way to attach the Tail Module with the Wing Module is to have an "arms extension" that will grab it side ways. It it then possible to assemble the two modules together connecting the electronic interface in a translational motion. This is shown in Figure 3.2 where two pins can be used to secure the two modules together. The dimension of the arm and pin have to be sized to sustain the separation forces that are to be determined.

Stress Considerations:

When a structure is submitted to an acceleration, the force felt by it will be its own inertia load plus the loads imposed by the masses it supports. Different materials such as aluminum, steel, titanium or composite materials all have different mechanical properties. One of them is density. Under an acceleration, the load felt by the structure is different for different materials that have different densities. The load on the structure also depends on the flyer’s equipment that have to be placed in the structure. These are the engine, the fuel, the batteries and all remaining electronics and hardware such as nuts and bolts and other miscellaneous parts.
Figure 3.2 is a computer generated schematic of the Tail Module.

![Tail Module Schematic]

**Figure 3.2: First Tail Module Design**

3.3.2 The Wing Module

The Wing Module is the middle module of the flyer. The components it contains are:

<table>
<thead>
<tr>
<th>Wing Module Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Power Converter</td>
</tr>
<tr>
<td>2. Batteries (LTC-511)</td>
</tr>
<tr>
<td>3. Fuel Tank</td>
</tr>
<tr>
<td>4. Wings</td>
</tr>
<tr>
<td>5. Wrap around GPS / Telemetry antenna</td>
</tr>
</tbody>
</table>

**Table 7: Wing Module Components**
Geometry considerations:

For all descriptions, please refer to Figure 3.3.

It was agreed with the wing team that their system would fit within a 130 mm long by 55 mm wide hole in the wing module. Their responsibility was to develop a wing and its associated deployment system that is as independent as possible from other system elements and linked only to the wing module by locking mechanisms such as bolts or screws.

Based on the first power demand estimation, five stacked high-g Eagle-Picher Lithium LTC-511 batteries were needed to power up the basics of the system for 40 minutes (no transmitter receiver for telemetry communication). Shown in Appendix B1 (list of components), they require a cylinder space of five cm by five cm and weigh 465 g. To simplify the on-board wiring and to group all electronics as much as possible, the batteries were chosen to be installed on the back face of the Wing Module, facing the Tail Module.

As a first guess, a 5 mm wall thickness is left in front of the batteries creating the aft wall of the wing box. The Motorola power converter (+5 V, +/- 12V and +/- 15V) is inserted above the batteries. All electronics are imbedded using the wax technic. As it was done for the Tail Module, the Wing Module electronics are sealed using a seal plate.

Above and below the wing box are two semi-cylindrical columns. On the bottom one, the gas tank is imbedded in the bottom column. Thus, some available volume is used to contain fuel and in addition, locating the gas tank below the wings would limit the Cg excursion as the fuel is used, crucial for the good autonomous control of the aircraft. The gas tank opening is sealed, at the forward end of the Wing Module by the engine support to which the Propulsion Module and engine connect.
Stress considerations:

Back-of-an-envelope calculations were done to estimate the wall thickness forward of the batteries to support the wing weight.

Figure 3.3: First Wing Module Design

3.3.3 The Propulsion Module

Geometry considerations:

The Propulsion Module consists of a cone that covers the engine and its starter system. As the flyer is inserted forward in the shell, the cone slope and length are determined by the shape of the front of the shell. A front hole in the cone is designed to accommodate a bearing to support the propeller shaft.
**Stress considerations:**

The Propulsion Module must support the rebound force of all the other modules as, in the worst case scenario, they decelerate at 4,000 g's. Therefore, the Propulsion Module must be strong and stiff enough to resist this load. Also, a heat balance study was required for proper venting as the two-stroke engine will generate considerable heat. The venting holes for the engine may induce additional stress concentrations and weak points in the design.

Finally, as discussed previously, the flyer must separate from the shell at deployment. The slope of the cone is critical since it can be pressfit in the shell under rebound load. As a good rule of thumb, the angle of the cone should be at least 16 deg to avoid pressfit of the flyer into the shell.

Figure 3.4 is a computer generated schematic of the Propulsion Module.

![Diagram of Propulsion Module](image)

**Figure 3.4: First Propulsion Module Design**
3.3.4 First Assembly in MK 64 Shell, Weight and Basic Stress Estimations

Appendix E2 is one of the first full-scale hand drawings of the assembly in the folded position. All above internal modules (lengths, datum lines etc.) were designed along with this drawing. A minimum shell back wall thickness was left based on the original MK64 base wall thickness. The aft of the tail module was set as the datum line.

3.3.4.1 Assembly Steps

Decomposing the flyer into different modules not only helps to define physical boundaries and to limit subsystems interactions but also determines the assembly steps. Assembly is critical and often hardware has to be designed directly with a possible assembly pattern in mind. In this first internal structure design, the assembly steps were:

Step 1: Tail Module assembly: connect all Tail Module electronics and secure them in their cavities using the hot glass bead liquid wax. Seal electronic cavities using the Seal Plate. Assemble tail pivot, servos and tail together and mount them in the Tail Module.

Step 2: Wing Module assembly: connect the batteries and the power regulator card using a printed circuit board and secure them using the hot liquid glass bead wax. Seal the electronic cavities using a seal plate. Insert the wing system in the Wing Module and secure it.

Step 3: Propulsion Module: assemble engine and engine starting mechanism on engine support. Secure them on Wing Module.

Step 4: Flyer assembly: assemble the Tail Module to the Wing Module and secure them. Attach the Propulsion Module to the Wing Module. Insert the flyer in the 5 inch shell.
3.3.4.2 Modification of the Shell

The choice of whether the team decides to modify a MK64 or a MK48 initially to fit the flyer is to be determined.

Available stocks for the MK 64 are large whereas the illuminating round body is not produced in volume. However, the Illuminating round already has a straight 3.9 inch diameter bore which is not the case in the conventional MK64 round designed to carry explosives. More machining is required if the team chooses to use the MK64 model. This will increase the cost and the difficulty to match desired tolerances along the length of the bore.

Since the MK64 blueprints were available, the team decided to develop the first flyer design based on its dimensions. A bore has to be created along most of the length of the shell. The front nose has to be machined at an angle to match the slope of the Propulsion Module. However, it was also clear that the MK48 option would reduce the amount of shell modification that would be required.

3.3.4.3 Choice of Material and Some Stress Estimations

In a high-g environment, a few approximate rules concerning choices of materials and types of structures are useful:

High-G Rules

1. The chosen material should be ductile and have a high yield strength
2. Stress concentration where deformation cannot be acceptable should be avoided
3. Avoid cantilever beams, a cellular structure is preferable
4. Take advantage of plastic flow and deformation to absorb energy

Table 8: Some High-G Rules

Also, in order to maximize the flyer aerodynamic performance and loiter time, it is important to minimize weight. Therefore, the goal is to aim for a light material still capable of surviving the high-g loading.
Creating an aluminum-composite structure could be possible but because of the short amount of time available for development, the team decided not to consider this option.

Among the common relatively low cost materials, aluminum has the lowest density (2789 kg/m³ or 0.098 lb/in³). For it to be acceptable as a structural material to the Tail Module, it must survive its own inertia loading plus the load imposed by the modules forward of it. Some approximated weights of various components are:

- Tail Module: 4.1 lb
- Wing Module: 3.36 lb
- Propulsion Cone: 0.09 lb

In addition, the wing weight is estimated to be around 1.65 lb, the engine-starting system around 1.5 lb, the batteries around 1 lb and the tails around 0.44 lb combined. Adding all electronics, servos, bolts and miscellaneous parts, another 4.4 lb should be taken into account. The total estimated mass is 16.54 lb (7.52 kg).

For safety factor considerations, the entire internal structure design was be developed for a set-back acceleration of 15,000 g’s (instead of 12,000) and a set-forward acceleration of 6,000 g’s (instead of 4,000). Also, the analysis always considered a constant loading, whereas in a real cannon launch the impulse force lasts for only about 20 ms. Finally, it was assumed that the compressive yield strength is comparable to the tensile strength of the material (even though for most isotropic materials compressive stress limits are much higher than tensile ones).
**Stress estimation:**

Not taking into account any stress concentrations, the determining surface is the aft end of the tail Module:

\[
\text{Area} = \pi \times \frac{3.9^2}{4} = 11.95 \text{in}^2
\]

\[
\sigma = \frac{F}{A} = \frac{(0.9 + 3.36 + 4.1 + 1.65 + 2.5 + 0.44 + 4.4)}{11.95} \times 15000 = 16.54 \frac{15000}{11.95}
\]

\[
\sigma = 20.8 \text{Ksi}
\]

The 7075-T6 aluminum alloy has a yield strength of 83 Ksi. Hence, as a first approximation, the area can be reduced by three in the Tail Module. The goal was then to avoid cross section areas getting under 3.98 in². As a first approximation using Pro-E, there are two critical areas: around the tail servo system and around the electronic and camera cavities. However, without considering any stress concentrations, the Tail Module passed the test.

At rebound, the load of the whole flyer is taken by the Propulsion Module. Shown in Figure 3.5, the stress area can be estimated to be the cone slope projected area.

![Figure 3.5: Rebound Stress Area](image)
Therefore:

\[
\sigma = \frac{F}{A} = 16.54 \times \frac{6000}{\frac{\pi}{4} (3.9^2 - 2.24^2)} = 12.4 \text{Ksi}
\]

There should be no problem for the Propulsion Module to survive rebound with a proper wall thickness. However, no stress concentration, wall friction force and possible bending forces were taken into account in the first design iteration.

The Tail Module and the Propulsion Module can both be made out of 7075-T6 aluminum as can the Wing Module. However, according to the basic high-g rules in Table 8, the choice of material violates argument #1 as the 7075 aluminum is not ductile. It will fracture easily where a stress concentration is present.

Finally, even though aluminum was acceptable for the flyer, there was some concern about choosing it for the structure. The shell is made out of forged steel heat treated near the base. The Young’s moduli of steel and aluminum differ greatly. Aluminum is less stiff than steel so under a constant acceleration, the two components (the shell and the flyer) will deform differently. This could induce radial reaction compressive stresses on the bottom part of the flyer. Also, a gap may appear between the Propulsion Module and the shell, leaving room for displacement and possible internal structure shattering at rebound.

3.3.4.4 Separation Mode Yet To Be Determined

No satisfactory flyer separation technique was yet identified. One of the assembly difficulties was that the shell had to be opened to insert the flyer, then closed for launch and survive the launch environment. Then, by some means, the shell must be re-opened to extract the flyer. Also, a parachute was required to slow the flyer from transonic speed to an appropriate operational velocity at which the wings can safely deploy. Therefore, additional internal space was needed to fit this parachute.
3.4 Tuning for Cg Location

To achieve the desired 10% static margin, the Cg of the flyer needed to be located at 24.5 cm from the base.

In order to survive the launch, the Tail Module required considerably more material because of the loads imposed by all the structures it must support. Therefore, the flyer base tended heavy, moving the Cg location towards the tail.

With the first internal structure design, the Cg location was determined as:

\[ X_{cg} = \frac{\sum Mass_i X_i}{\sum Mass_i} \]

Using Pro-E, the volumes, masses and center of mass of each module were determined. If the entire flyer was made out of aluminum, the Cg location of the flyer would be at 18.9 cm from the base. The goal was to change the material of the cone or change its shape and wall thicknesses to bring the Cg to 24.5 cm from the base.

So:

\[ X_{cg\text{ desired}} = \frac{2.508(4.18) + 8.36(3.43) + 9.84(2.2) + 14.57(0.88) + \rho_c V_c C_g c}{4.18 + 3.433 + 2.2 + 0.88 + \rho_c V_c} \]

Leaving the cone volume and density as variables enable the Cg to be located by trial and error. First the density was changed from aluminum to steel (from 0.098 lb/inch\(^3\) to 0.285 lb/in\(^3\)) and with the geometry constant, the Cg location moved to 21.7 cm from the base. This was clearly not enough. To attain 24.5 cm, the wall thickness and the internal geometry of the Propulsion Module had to change. In doing so and using steel, the weight of the flyer increased to more than 20 lbs, penalizing the aerodynamic and loiter performance. Also, a heavier cone induced higher stresses in all modules.

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This Cg estimation was not exact because many component weights are estimated, but it provided a reasonable approximation of where the Cg would be located. The current first design configuration was not optimal and a second design iteration was needed.

3.5 First Inertia Model

With the help of the CAD package, the inertia tensors for all modules were calculated. However, the wings and some other parts were not yet modeled on Pro-E. Therefore, the wing inertias had to be calculated by hand approximating them as a one meter long 800 grams rod. The inertias of the two tails are also calculated in the same axis and all inertias were referenced on the desired 24.5 cm Cg location and added using the Parallel Axis Theorem. Figure 3.6 shows the WASP coordinate axis frame.

![Figure 3.6: WASP Coordinate Axis](image)

After calculations, the inertia tensor is (in lbs.in²):

\[
\begin{bmatrix}
604 & 0 & 3.96 \\
0 & 307.7 & 0 \\
3.96 & 0 & 896.8
\end{bmatrix} =
\begin{bmatrix}
Ixx & Ixy & Ixz \\
Iyx & Iyy & Iyz \\
Izx & Izy & Izz
\end{bmatrix}
\]
The zero cross terms are not really zero but small enough to be neglected. Also, it can be noted that the flyer has a larger inertia in the pitch axis than in roll, even though the wings extend 50cm on each side of the structure. Major modifications were still necessary to improve the design and achieve an acceptable Cg location. These modifications could change the inertia tensor just described.

The following figure is an exploded view of the first internal structure. A preliminary cut in the Propulsion Module for engine cooling is included in the diagram.

![Figure 3.7: First Internal Structure Design](image)

3.6 Use of the First Internal Structure Design

A StereoLithography (STL) plastic model of the entire internal structure was built using this first design. It enabled the team to visualize the flyer assembly and to determine some assembly and machining problems.

The plastic model was also very useful for determining some aerodynamic properties. Mounted as shown in Figure 3.8 in a five by seven foot open section Wind Tunnel, body drag of the flyer at different angles-of-attack was measured using the full-scale STL article.
Figure 3.8: STL Model Used to Determine Flyer Body Drag

The experimental drag was found to be twice as high as the analytical drag\(^{(4)}\). Overall drag and engine power requirements were rapidly updated.
CHAPTER 4

DESIGN OF TAIL MODULE MECHANICAL SYSTEMS

4.1 Control Effectors Mechanism

4.1.1 Technical Requirements

The two tails inclined at 35 deg. from the horizontal are the only control surfaces of the WASP flyer. They are inclined downwards to induce a yaw moment if deflected deferentially, leading the flyer into a banked turn. Similarly, deflecting both tails up or down produces pitch moments. The control effectors affect the stability and control of the flyer in the yaw, pitch and roll axes playing the role of a combined rudder and elevator. The size of the tails is also related to the span of the wings, their position and the position of the flyer Cg.

To control the aircraft, the tails need to rotate about an axis for a certain angle determined by the control requirements. It is also important to minimize trim angle as a large angle can generate more trim drag.

The control mechanisms for the tails have to survive the launch accelerations and still be able to deploy properly and rotate freely. The design of the tails is also very dependent upon the Tail Module geometry since the tails, the servos and the entire control mechanism have to be imbedded in the structure. An additional difficulty is that to maximize the distance between the Cg and the tails, the pivot axis and control mechanism have to be located at the base of the flyer, where maximum load exist.
4.1.2 Mechanism Brainstorming

The goal was to design two deployable and controllable tails, located as far as possible from the flyer Cg. One idea was to deploy the tails behind the Tail Module using a telescopic motion. This option was looked into by the wing team as they explored the “Telescopic Wing” for wing deployment. It appeared to be high risk due to complexity and possible mechanism\(^4\) jamming.

To reduce the mission failure probability, it was agreed that the tail system deployment mechanism should be as simple as possible. The design had to 1) successfully survive the launch acceleration, 2) separate and slow down from transonic speeds, 3) deploy one meter span wings from a 3.9 inch diameter structure and 4) deploy a propeller and demonstrate a successful engine start. So, the tail must not add complexity. As described in Chapter 3, a simple passive swinging tail design was chosen for deployment.

The two rotating tails are spring-loaded as they are folded in the Tail Module (see Chapter 3 for geometric description). The tails would be restrained by the shell internal wall while the flyer is stowed. As soon as the flyer is extracted from the shell, the tails would be free to deploy, both making a rotation of 90 deg. around their deployment axes.

4.2 Design of Control Effector Mechanisms and Integration in Tail Module

4.2.1 Tail Geometry and Profile

Starting from the tail mechanism brainstorming shown in Appendix E2, the goal was to first determine the appropriate tail profile to minimize drag and still survive the g-loading. Then, a passive deployment mechanism linked to a control mechanism was designed.
4.2.1.1 Tail Profile Determination

Using an airfoil analysis software code, the wing team selected the NACA 1415 for the tail profile\(^4\). With 10.5 cm long tails, one meter span wings and the desired first design iteration Cg position, a trim angle of 4 degrees was initially needed to stabilized the WASP flyer.

A significant advantage of this relatively thick airfoil is that the tail had a greater chance to survive launch acceleration. Five inch Air Gun experimental testing on the foldable wing concept preliminary design had shown limits on trailing edge thicknesses and buckling problems\(^4\). Therefore, it was agreed that the NACA1415 profile was a good profile for this application.

4.2.1.2 Passive Deployment Mechanism Design

*Geometric concerns:*

Figure 4.1 is a top view of one of the tails. When folded, its leading edge rests against the inner wall of the Tail Module cut and its trailing edge against the inner wall of the shell internal bore. A pivot point is necessary around which the tail will rotate to deploy. To gain the maximum possible "storing" length in the Tail Module, the pivot point has to be located near the tail trailing edge.

This pivot point is also the point about which the tail will be rotated in order to control the aircraft. The servo-motors will have to overcome the torque induced by the aerodynamic loads on the tail surface. Also, this tail-pivot geometry could lead to instabilities as aeroelastic effects may be introduced if there is an insufficient stiffness. However, for the prototype design, this solution should still be acceptable as it is possible to design sufficiently stiff tail surfaces. Improvements are possible and will be discussed later.
Appendix F contains sketches of the tail-pivot assembly. The pivot is a small cylinder with a groove in which the tail gets inserted. A torsion spring and a pin links the tail and the pivot together. The torsion spring is loaded as the tail is folded in the Tail Module. The pivot is itself inserted in the Tail Module and is responsible for control of the surfaces as the servo-motors are activated. Figure 4.2 is an assembly view of the tail-pivot assembly.
Stress concerns:

a) Weight:

The weight of the tail has to be determined prior to any stress calculation. As mentioned previously, the tail profile has a chord of 4.5 cm, a length of 10.5 cm and a maximum thickness of 5/16 inch (0.8 cm). Approximating the tails as a rectangle, its mass is slightly over estimated mass as $W_{tail} = 105 \text{ g}$.

b) Pin shear stress and tail bearing stress:

With the tail folded into the Tail Module, it is assumed that during launch the load imposed by the mass of the tail surface will be borne by the pivot pin only and no other structures will carry a portion of the load.

The pin diameter is $13/64^{th}$ inches or 5.15 mm.

$$\sigma = \frac{F}{A} = \frac{15000 \times 9.81 \times 0.105}{2 \times \frac{\Pi \times (5.15 \times 10^{-3})^2}{4}} = 370 \text{ Mpa}$$

The shear force on the pin is divided by two pin cross section areas. Therefore, using an oil-quenched heat-treated steel pin, yield strength can exceed 700 Mpa and still not be too brittle to absorb shock energy with a safety factor of about two. Rebound stress should be three times lower.

In Figure 4.2 above, a torsion spring is imbedded between the tail and the pivot it-self. This geometry (considering spring size) leaves 4 mm of bearing metal.
Therefore, the bearing stress of the tail around the pin is:

\[
\sigma = \frac{F}{A} = \frac{15000 \times 9.81 \times 0.105}{5.15 \times 10^{-3} \times 4 \times 10^{-3}} = 750 \text{MPa}
\]

This stress result is above the yield strength of 7075-T6 aluminum (576 MPa). A heat treated steel bushing insert may be considered to harden the bearing surface area. With the pin hole, 1.772e-5 m² of material (minimum) is left on either side. At rebound:

\[
\sigma = \frac{F}{A} = \frac{4000 \times 9.81 \times 0.105}{2 \times 1.772 \times 10^{-5}} = 116 \text{MPa}
\]

With no heat treated bushing, the stresses at rebound should be acceptable (safety factor of almost 5).

c) Launch and aerodynamic bending moments:

The design of the vehicle avoids bending moments at launch. The tails are situated longitudinally in the Tail Module and the entire load is assumed to be carried by the pivot steel pin. Even if the contact between the tail and the pin is off-centered (see Figure 4.2), no moment should be felt by the pin.

After launch, the tails will deploy passively as the flyer is extracted from the shell. This will occur at transonic speeds hence the tail loads must be determined at that speed. It is assumed that the tails deploy and see sonic flow facing their entire surface area.
Figure 4.3: Sketch of Tail Facing Sonic Flow

So:

\[ A_{\text{frontal}} = 4.515 \times 10^{-3} \]

\[ F = \frac{1}{2} C_d A V^2 = 0.5 \times 1.1 \times 4.515 \times 10^{-3} \times 350^2 = 304.2 N \]

Assuming that the tail is a rectangle, that the max thickness of the profile is 15% of the chord (45mm) hence 6.75mm, and that the minimum thickness (trailing edge design) is 13 mm, the Moment of Inertia for the average thickness is:

\[ I = \frac{1}{12} b h^3 = \frac{1}{12} \times 0.105 \times 0.004025^3 = 5.7 \times 10^{-10} \]

The average over estimated stress is (since it was decided to concentrate the aerodynamic load at the tip of the tail and not distributed as it should be):

\[ \sigma = \frac{F d z}{I} = \frac{304 \times 0.105 \times \frac{0.00675}{2}}{5.7 \times 10^{-10}} = 189 \text{MPa} \]
Therefore, aerodynamic loading is acceptable at deployment and hence in operational conditions where the speeds are in the order of 100 mph.

d) Geometric help for load bearing in the Tail Module:

Basic stress analysis on the tail pivot was done assuming that only the pin would take the load. However, additional load bearing surfaces should help decrease the stress on the pivot.

![Figure 4.4: Tail Design and Load Bearing Surfaces](image)

As shown in Figure 4.4, the Cg of the tail is off-centered from the pin axis. At launch, its leading edge will rest against the inner wall of the Tail Module tail cut. Also, the bottom of the tail will partly be rested against a Tail Module inner wall hence providing a load path.

All above calculations were done using an overestimated weight of 105 grams. The real mass of each tail is 89 grams. This “extra” design weight leaves a bit of leeway if the tails have to be elongated for aerodynamic stability reasons.
4.2.2 Choice of Servos

The choice of servos\(^7\) and the design of the control mechanism were done concurrently as the whole system had to fit within the remaining Tail Module space.

Many precision servo-motors from different companies were examined. The concern was to find servos that were compact, small and strong enough to rotate the tails, at operational speeds, and also survive 15,000 g's of acceleration. No available precision servo-motors were found to be satisfactory and custom made ones could seriously postpone the project’s deadline and consume a large part of the available resources.

Scale modeling servos were never yet been looked into for high-g applications. According to the wing and control teams, the tails had to rotate plus or minus 8 deg. to be operational. The NACA 1415 profile generates a moment of 0.096Nm at 80 m/s (above operational speed) at the pivot. Using an appropriate reduction mechanism, some off-the-shelf RC (Remote Control) Model servos could do the job as their speed, torque and size were sufficient. The question was to determine if they would survive 15,000 g's!

Preparation of the servos for experimental testing:

RC Model servos are composed of a small reduction gearbox and an electronic compartment that contains a control card, a small electric motor, and a potentiometer linked to the gears for position feedback loop. All elements are very light (including the gears which are plastic) and thus have a great potential to survive high-g's. The approach was to lock all electronic components in place and to provide support for the small electronic card in the servos by poring the Glass Bead Wax into all empty cavities (except where the gears mesh).

Three different off-the-shelf servos were purchased: one micro, one with a coreless electric motor (middle torque output), plastic gears and no bearing and a third one having the larger torque output with a coreless motor, one metal gear and a bearing. The first two of these were g-hardened
using the wax method described earlier and they were imbedded in an aluminum test block, as they would be imbedded in the Tail Module.

![A Servo Cavity

Figure 4.5: Servos Test Article

When inserted in the cavities, all servo surfaces must be supported. The cavity must be sized and machined to the servo dimensions and the extra space must be filled with wax. In doing so, they are constrained not to move in any direction. Shown in Figure 4.5 is the servo test article.

This test article was inserted in a five inch Test Canister and the assembly was shot from a five inch Air Gun at Picatinny Arsenal (more details about the tests will be given in the next chapter as experimental testing was done to verify the Tail Module/tails assembly).

*Experimental results:*

The two g-hardened servos survived up to 20,000 g! The third non g-hardened servo failed. The electronic card moved and the casing of the small electric motor detached from a point where the brushes are located. Also, because the electric motor in the third model (highest output torque model) is heavier than for the two other smaller models, the plastic wall separating the electronics from the gear system deformed and cracked.

The servo-motors have a plus or minus 30 deg. of range and the tails have to move at least plus or minus 8 deg. to satisfy the control requirements. To design for plus or minus 10 deg. a reduc-
tion mechanism is needed. The idea was to use a mechanical diode that could lock the tail in place where desired, thus reducing the load from the servos as much as possible. Using a Worm / Worm-Gear assembly, it is possible to do so and to locate the servo-motors 90 deg. off the tail rotation axis (hence in the desired length of the Tail Module) so that they could fit in the 3.9 inch flyer diameter. With the appropriate servos, four times more torque than required can be obtained(7).
CHAPTER 5

INTERNAL STRUCTURE 2\textsuperscript{nd} DESIGN ITERATION

5.1 New Evaluation of WASP Subsystems

The first internal structure design was very useful as it helped all the teams to refine and integrate their designs. As mentioned previously, a StereoLithography model was made to help physically visualize the prototype and to determine body drag through Wind Tunnel Testing. In addition, more and more information about individual components, subsystems characteristics and machining facilities was obtained and analyzed leading to the 2\textsuperscript{nd} internal structure design iteration.

5.1.1 Parachute Subsystem

Ideas such as pulling up and gaining potential energy to slow the flyer down after separation were discussed but the illuminating round concept, incorporating the parachute idea, was retained. One of the problems the team was faced with was a severe volume constraint. As shown in Figure 2.10 in Chapter 2, the illuminating round parachute and drogue chute occupy more than one half of the total internal shell volume. The parachute needs to be large to maximize the flare flight time and a drogue chute is used to initiate the deployment of the main parachute.

The first iteration WASP flyer occupied almost the entire shell internal volume. Also, the parachute will have to be attached to the aft end of the flyer and the parachute itself should not be crushed by the weight of the flyer at launch. Significant questions were: how large should the parachute be? How should it be stored and how small can it be safely folded to maximize volume usage?
It was decided that only one parachute would be used to decelerate the flyer from transonic speeds to operational speeds. The vehicle terminal velocity had to be a trade off between wing maximum acceptable dynamic pressure for deployment and internal volume usage. For a chosen 270 ft./s terminal velocity and an overestimated flyer weight of 22 lb, a small one foot diameter kevlar parachute could do the job. Well folded, it can fit within 10 inch$^3$ and when deployed, it can bring the WASP to 270 ft./s in 15 seconds$^2$. For the design and the manufacturing of the parachute, the team consulted Butler Parachute Inc. Three similar “Cross Design” Non-Despinning parachutes were delivered. Figure 5.1 is a photograph of one of the parachutes deployed during a low-speed wind tunnel testing.

![Figure 5.1 Non-Despinning Cross Design WASP Parachute](image)

The parachute still had to be mechanically deployed and attached to the aft end of the flyer. These will be detailed below in section 5.1.5.

5.1.2 New Wing Location and Tail Length

As described in Chapter 3, designing for the Cg location to be at 24.5 cm from the base required a large addition of lumped mass in the front part of the flyer. This was not efficient since more mass means reduced flight performance and higher structural loads at launch.

Since the span of the wings was limited, one solution was to move the entire wing assembly back in the flyer. Moving the wings back also means allowing the Cg position to move backwards
for marginally stable flight. However, for controllability and acceptable trim angles, moving the wings back also required lengthening the tails to compensate for the loss of tail moment arm.

The wings were moved backwards and the tails lengthened. In the first internal structure design, a 5 cm long compartment behind the wings was designated to fit the g-hardened Eagle-Picher LTC-511 batteries. Therefore, it was agreed that the wings should move 4 cm backwards, the tails lengthen 1 cm, and the batteries should move in front of the Wing Box Cavity, extending 1 cm into the Propulsion Module. Doing so, the Cg should be located at 20.6 cm from the base for a 10% static margin. Ballast in the nose was considerably reduced and flying performance enhanced.

5.1.3 Propulsion Unit System

The propulsion system consists primarily of a two stroke engine, its starting and throttle control mechanisms. Experiments showed that a spring start system worked well. The propulsion team developed a high-g spring start system for an O.S FP 15 two-stroke engine providing 0.45 hp. The flyer requires 0.6 hp to achieve level flight and would therefore be slightly underpowered, but the volume constraint was a major factor. Future work could be done to increase the power of this small engine to allow level flight.

This engine was tested in the 5 inch Air Gun at 15,000 G’s and no internal deformation or failures were observed. However the carburetor sheared off at its base but no internal parts such as the needle were deformed. With a new carburetor in place, the engine was re-started without any anomalies. An O.S Wankel engine was also tested but a bearing casing failed and jammed the rotating triangular piston.

A folding propeller was also designed and because the engine starting was such a risky issue, a 500W AVEOX three phase electric motor was chosen as a fall back. The Propulsion Module design had to accommodate all of the above and still survive the rebound loads as it will be crushed forward by the two other remaining modules.
5.1.4 Batteries

The entire WASP HGV was conceived to be as close as possible to the final Operational Vehicle. Battery technology is lagging behind other domains and no really efficient power cells yet exist. Five LTC-511 high-g batteries could only supply four minutes of powered flight if all systems such as computer, IMU, GPS and transmitter / receiver have to be activated.

A WASP Power Consumption study was conducted\(^7\). High-g battery choice being limited, an estimation of different off-the-shelf batteries enabled the team to select a couple of them for different possible flight durations, internal volume space and fuel-batteries space trade off.

Different types of batteries were shot at 15,000 g's using the 5 inch Air Gun. All Ni-Cad batteries completely failed. No output voltage was measured after the test. One Solar Inc. 1200mah 1.2 V did survive 12,000 g's but failed the test at 15,000 (two samples).

It was agreed to design for those Solar Inc. batteries as they have conventional AA commercial size. Explained below in the Wing Module section 5.2.3, the battery / fuel tank compartment dimensions make it possible to fit conventional, or LTC batteries, fuel or no fuel tank depending on the mission and the on-board power requirements.
5.1.5 The Camera

The high-g camera manufacturer Xybion decided not to develop an adequate camera to suit the WASP application. Along with the servos and the batteries and other important pieces of hardware, two different off-the-shelf micro cameras that might survive the high-g’s were tested. Shot from the 5 inch Air Gun, they both survived 15,000 g’s because they were mounted appropriately and imbedded in the wax. Figure 5.3 is a photograph of the two micro cameras with their experimental mounting bed.

![Figure 5.3: Off-The-Shelf Cameras](image)

The design of the new internal structure does not have any cavity for those cameras as they were one of the last tested items.
5.1.6 The Separation Technique

Using the proven illuminating round projectile body, the WASP flyer is extracted from the back of the shell. A choice was made to use the MOD 48 MkI illuminating round shell as the Navy agreed to donate three inert shells and the blueprints.

The question was how to close the back end of the shell so that it can survive the launch loads with the flyer pushing on it at rebound (worst case scenario) and still be able to get rid of this back part to extract the flyer from the shell when separation was desired. In a conventional illuminating round, the fuse is connected to a charge that detonates and creates enough pressure to depressfit the Back End (shaped as a plug), shearing some retaining pins and pushing out the internal canister from the shell. Actually, there is a small clearance gap between the internal parachute / illuminating powder canister and the walls of the shell to allow the pressure to build up and push directly on the Back End hence not transmitting the pressure force through the canister. A front charge was first considered, but complications occurred as to how to protect the engine compartment in the Propulsion Module from the flame and as to how to fit this charge in the restrained internal volume. What’s more, it was found that at extraction, the parachute would take about 0.25s to fully deploy and that the WASP flyer with no pulling parachute force could tumble in 0.2 s\(^2\) due to static instabilities.

Therefore, among many ideas, the team finally agreed to attach the Back End assembly to the main shell body using a two ring collar\(^8\). The flyer is itself attached to the Back End on which Smart Active Laser Guided Projectile (SAL-GP) supersonic fins are mounted. The parachute fits in this Back End and a Parachute cover plate is used to seal the parachute cavity at launch to protect it from the high pressures and heat. At separation, this same cover plate is used to extract the parachute from its cavity with two custom made explosive pushers that throw the plate away with 1000lb of force. At the same time, a linear shaped charge located in the Back End and under the collar will cut the collar, freeing the main shell body. The parachute has enough force\(^2\) to pull out the Back End with the attached WASP flyer, the whole assembly being aerodynamically stable.
as the supersonic fins are still attached. An exploded view of the Back End design is shown in Figure 5.4.

![Figure 5.4: The Back End Shell Assembly](image)

The Back End geometry and dimensions determine the shape of the aft end of the Tail Module.

### 5.2 Second Internal Structure Design

#### 5.2.1 DFMA Considerations

The first internal structure was developed to fit all WASP necessary components in the given internal shell volume. The design used basic modularity and assembly ideas but it was not refined in terms of machining and manufacturing. One of the main goals of the second internal structure design, was to apply basic "Design For Manufacturing and Assembly" or DFMA rules. In summary, these are:
Basic DFMA Rules

1. Simplify and reduce the number of parts
2. Standardize and use common parts and materials
3. Design for ease of fabrication and machining
4. Design for ease of assembly
5. Design for efficient joining and fastening
6. Design modular products

Table 9: DFMA Summary Rules

All cavities should be machinable using conventional tooling such as mill, lathe and drill bits. All design radii should be standard tool radiiuses and all cut lengths should be below shank lengths to minimize machining time.

5.2.2 The Tail Module

5.2.2.1 New Design

Shown in Figure 5.5, the Tail Module was divided in three main parts: the Electric Insert, the Tail Module body and the Male Plate.

Figure 5.5: The New Tail Module Design
The Tail Module body has two 1.9 inch deep pockets to receive the two RC servo controllers. Along its length are, two 5/16 inch wide cuts to allow the two tails to be folded within the module.

The Male Plate is the aft end of the WASP flyer. Two protrusions on the Male Plate will, when assembled with the Tail Module body, close the servo cavities, preventing them from moving in any direction. Appropriate clearances are left for tuning and wax potting. Also, to attach the flyer to the Back End, a 0.5 inch explosive bolt passes through and extends behind the Male Plate at its center. The head of the explosive bolt is sandwiched between the Tail Module and the Male Plate and sits in a cut, shaped the size of the bolt head.

The control effector mechanism is composed of a worm / worm-gear assembly. An off-the-shelf precision worm gear is modified so it can be attached to the pivot and fixed in place with a flat head set screw. Its corresponding worm is also modified to fit on the servo and is held in place at its other end by a shoulder bolt and the Male Plate. Doing so, the worm is restrained to move in all directions. The shoulder is sized to restrain it to move forward in the servo at rebound. Another shoulder bolt is used to prevent the pivot from sliding out the cavity in which it rotates.

At a point in time after the Tail Module had been machined, the wing and the control teams realized that it would not be possible to efficiently control the WASP flyer since it was marginally stable in yaw. To solve the problem, two passive fins (one on top, and one on the bottom) had to be added to the Tail Module. The largest fins possible (according to the geometry) were designed to deploy in the same way that the tails do. To fold them in the Tail Module, two very thin cuts were machined using an Electro Discharge Machining (EDM) technique. EDM, which uses a carbon electrode to vaporize the metal, is expensive and does not correspond to the notion of Standard Tooling the team wanted to stick too. To limit the cost, a standard 1/8" electrode width was used to cut 1.5 inch deep, the passive fins being 0.1 inch thick and 1.5 inch of chord.
5.2.2.2 Stress Analysis

Because of the complex Tail Module geometry, stress analysis using a FEM software was necessary.

The loads

The Electric Insert, the Tail Module main body and the Male Plate are considered to be one single entity. For the analysis, the loads were 6kg times 15,000 g’s to simulate the weight of the Wing and Propulsion modules plus the Tail Module inertia. The only constraint is no displacement of the bottom surface. All other deformation is allowed in all directions. The team is not counting on the shell to prevent any internal structure Poisson’s deformation.

The results

Figure 5.6 and 5.7 below are two views of the Tail Module graphical stress analysis results using ANSYS, where stresses appeared to be maximum. All electronic cavities are filled with wax, which behaves like an incompressible fluid.
Figure 5.6: Tail Module Side Cut Stress Analysis

Figure 5.7: Tail Module Electric Insert Stress Analysis
Maximum stress of 90,000 ksi is located on the corner part of the tail cut and at certain points on the surface of the electric insert where the load of the other modules is applied. Using 7075-T6 aluminum which has a yield strength of 83,000 ksi, those stress concentrations are slightly above yield. However, considering that the remaining stresses are acceptable (average of 42,000 ksi) and that this cut can be allowed to deform, the overall stress pattern is judged to be safe.

However, the original hole for the camera in the Tail Module had to be removed. When iterating for appropriate stresses, the provided camera hole caused too high a stress concentration. The entire Tail Module failed under the load of the other above modules. The camera location had to moved to the Wing Module, slightly complicating the wire connections.

Finally, the electronic components will heat during operation. Heat will have to be adequately transferred to the flyer body which will serve as a heat sink. A certain wax thermal expansion is also considered and stresses caused by this expansion (100 deg F elevation) are also verified using FEM. In general, if appropriate heat transfer to the flyer body is provided, no dramatic stress levels are observed.

**Male Plate Bolt Retaining Calculations:**

Four 10-32 alloy hex bolts are used to attach the Male Plate to the Tail Module. They are sized safely to the maximum parachute pulling load at deployment of 600 lb\(^{(2)}\) (from drag estimation). The explosive bolt designed by Special Devices Incorporated (SDI) has a maximum working force of 19,000 lb.

**5.2.2.3 Experimental Testing**

In Chapter 2, it was shown that in a gun launch, the three main load concerns were the setback force, the rebound and the blast stochastic input force that excites the projectile assembly vibrational modes. To test for the first load concern, the five inch Air Gun test is a very useful experimental apparatus as it can impart very high g's to experimental specimens. Luckily, the US
Army agreed to sponsor the team for 28 shots (US $1,000 per shot) since they were interested by the project's potential results.

*The five inch Air Gun Apparatus:*

The five inch Air Gun experimental apparatus is located in New Jersey at the US Army Picatinny Arsenal. Shown in Figure 5.8, the Air Gun consists in a 1916 era five inch gun that is modified to have its powder chamber pressurized with air pumped by compressors and boosters up to 25,000 psi. A five inch aluminum canister that contains the experimental specimen is inserted by the breech opening and enclosed by the breechlock as in a normal gun. The barrel is connected to a five inch long tube that is pressurized up to 200 psi to slow down the canister when it is shot. To determine the g-loading, the canister with its experimental specimen are weighed and an appropriate aluminum diaphragm is locked on the canister by a large nut. This diaphragm shears at a certain pressure, releasing the canister into the barrel.

![Figure 5.8: The 5 inch Picatinny Air Gun](image)

An accelerometer is also installed on the canister and its wire is run along a certain length of the tube and exits from it to be connected to an Analog to Digital converter and to a computer system.
The Tail Module Experimental Set-up:

The entire Tail Module including a servos, a worm and a complete Tail-Pivot assembly was inserted in a custom made five inch test canister. A lumped steel mass of 2.2 kg was placed on top of the Electronic Insert to simulate part of the rest of the flyer launch load. A desired 6 kg mass could not fit in the canister.

![Figure 5.9: The Tail Module Experimental Specimen](image)

Figure 5.9 is a photograph of the experimental Tail Module assembly.

The Tail Module Experimental results:

The Tail Module and its components have all survived up to 16,300 g’s, which was the maximum the Air Gun could give out considering the weight of the experimental specimen! Three shots in total were done: the first around 5000 g’s, the second at 12,000 and the last one at 16,300 g’s.
Between each shot, the canister was opened and the Tail Module was extracted from it. Each time, the tail deployed easily and no sign of buckling, shear or cracks on the tail were observed. A small crack was however observed in the bottom of the empty servo cavity where the wall thickness between the Electric Insert and the servo is quite thin. The other servo cavity which contained the servos imbedded in wax showed not sign of crack or deformation. Table 10 summarizes the experimental results.

<table>
<thead>
<tr>
<th>Test#</th>
<th>G Loading</th>
<th>Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4,900</td>
<td>OK</td>
</tr>
<tr>
<td>2</td>
<td>12,500</td>
<td>OK</td>
</tr>
<tr>
<td>3</td>
<td>16,300</td>
<td>Small crack in bottom of empty servo cavity</td>
</tr>
</tbody>
</table>

Table 10: Tail Module Experimental Results

Appendix G provides the accelerometer readings for the three shots. There is a large discrepancy between the diaphragm bursting g-calculations and those readings. Based on past Picatinny Arsenal operators’ past experience, the diaphragm calculations should be more reliable and those accelerometer readings were therefore considered with caution.

*Air Gun proof concern:*

These results are very encouraging as the first step towards the complete WASP assembly has been accomplished. However, there is still a concern about the proof of the Air Gun with respect to a real gun launch. As one can see in Appendix G, the difference between the Air Gun and a standard five inch gun is the duration of the pulse. The Air Gun has a pulse duration of 2 ms whereas the real gun has a pulse duration of 20 ms. This comparison is illustrated in Appendix H. In terms of energy, that would be the integral under the curve, and the real gun will deliver much more energy to the specimen. Therefore, even though higher g’s can be attained using the Air Gun, the effect of the shock may be weaker than in a real gun launch.
5.2.3 Wing Module
5.2.3.1 New Design

The Module

Figure 5.10 is a schematic of the new Wing Module. The front part of the module has a 2.9 inch cylindrical cavity in which the fuel tank and the batteries are located. The Wing Box was moved 4 cm backwards, according to what was discussed in section 5.1.2. The joint between the Tail Module and the Wing Module was changed and their connection is now accomplished using four 10-32 28 UNF flat head alloy bolts through the Tail Module lip.

![Figure 5.10: The Wing Module](image)

The battery and fuel tank cavity will be sealed by the Propulsion Module and the Engine Mounting Plate. The front cone of the Propulsion Module screws on the threaded 28 UNF lip that extends from the front of the Wing Module.

The Inserted High G Folding Wings

The goal was to design one meter span wings that could fold efficiently into a 3.9 inch diameter cylinder and still survive the 15,000 g set-back acceleration and the 4,000 g’s rebound force. On each side of the structure, six wing segments are folded to make a compact high-g resistant
mechanical entity. At deployment, the two spring-loaded folded wings pivot out from the flyer body allowing the wings to further deploy as shown in 5.11.

![Figure 5.11: WASP Foldable High-G Wings](image1)

When completely folded, the high-g wing system is inserted in the Wing Module as shown in Figure 5.12.

![Figure 5.12: High-G Wings Inserted in Wing Module](image2)

The wings are restrained to the Wing Module by four 1/4 inch fine thread hex alloy allen bolts. Also, a rounded block is bolted through the gas tank and battery cavity bottom wall to help the wings survive rebound forces as it will prevent their displacement and shear of some hinges.
5.2.3.2 Stress Analysis

The loads:

Three major loads have to be considered. These are the Propulsion Module weight, the weight of the batteries and fuel tank supported by a wall thickness just above the Wing Box hole, and the wing system. The weight of the wings is estimated to be 750 g, the propulsion module is about 2 kg and the batteries combined with the fuel tank and fuel are estimated to be 500 g.

The results:

Figure 5.13 and 5.14 are stress and displacement results for the Wing Module at 15,000 g’s. The overall stress level is less then half the yield strength of the 7075-T6 aluminum. High stress concentrations (above 95,000 psi) are observed in localized regions where the Wing Module tail cuts are but should not affect the structural integrity of the entire module. Maximum displacement is acceptable (0.013 inch) and the wings will not be crushed by the deformation of the module at launch.
As mentioned in the new Tail Module design in section 5.2.2.2, the original camera location had to move because stresses were too high in this aft end region. According to the stress level around the Wing Box in the Wing Module, the small cameras discussed in Section 5.1.5 could certainly be placed under the wings.
The bottom wall thickness of the batteries and fuel tank cavity have been dimensioned to support 500 g at 15,000 g's. The required wall thickness found is approximately 5 mm. FEM modeling is used to verify the design.

![Figure 5.15: Bottom Batteries and Fuel Tank Wall Thickness Stresses](image)

Stresses in Figure 5.15 (36,000 ksi) are half the material yield strength. The chosen wall thickness can therefore safely support the required battery and fuel tank launch loads. However, the wing team needed some last minute modifications on the wing system for it to survive rebound. To simplify the Wing Module machining process, a wing rebound block had to be bolted to the Wing Module through the bottom of the battery and fuel tank cavity. (which was not designed for in the first place). Using two flat head alloy bolts, the block will exert an additional force on the wall thickness. Stresses should still be under the material yield stress, and well under the 1.5 safety factor as well.

*Bolt Calculations for Wings and Wing Block:*

The entire wing system (750 g) is restrained for rebound using four 1/4 inch 28 UNF by 0.5 inch long hex alloy allen bolts. Similarly, the rounded block that prevents possible wing displacement in rebound, is attached to the Wing Module using two 1/4 inch 28 UNF 0.5 inch long flat head alloy bolts.
5.2.3.3 Experimental Testing

_The Wing Module Experimental Set-Up:_

As was the case for the Tail Module, the Wing Module was tested in the five inch Air Gun and it was primarily used to support the high-g foldable wings. The experimental set-up included the wings, the Wing Module and one of the five inch Air Gun test canisters used to carry the specimens in the five inch Air Gun.

_The Wing Module Experimental Results:_

Three shots in total were done. The whole assembly plus the Wings resisted up to 14,600 g's in set-back acceleration and 4,000 g's in rebound (the specimen was inverted in the canister to test rebound). Both, the Wings and the Wing Module showed no sign of cracks or local failures. This result was especially remarkable for the wings that were developed step by step essentially based on experimental testing\(^4\).
5.2.4 The Propulsion Module

5.2.4.1 New Design

The Propulsion Module components include the engine, its starting mechanism, the engine mounting plate and the exterior cone. Figure 5.16 is an exploded view of the module.

![Exploded View Of The Propulsion Module](image)

**Figure 5.16: Exploded View Of The Propulsion Module**

The load bearing component at rebound is the cone. As stated in Chapter 3, the slope angle of the cone should be at least 16 degrees to avoid any pressfit situation. In the design, the angle is set to 19 degrees. To reduce any further pressfit risk, a step is also designed into the cone to take rebound. Two lateral slanted cuts are grooved into the cone to leave room to the propeller to be folded in the shell. The propeller deploys passively as soon as the WASP flyer is extracted from the shell. Those cuts combined with an oval groove above the head of the engine provide cooling. To secure the Propulsion Module to the rest of the flyer, the cone is screwed to the Wing Module using a 28 UNF thread and the engine mounting is held in place between the cone and the front part of the Wing Module. Figure 5.17 illustrates the design of the joint, transmitting the rebound load axially from the Propulsion Module to the Wing Module.
Figure 5.17: Sketch Of Wing Module / Propulsion Module Joint

The front part of the MK 48 MOD I shell is modified\(^{(8)}\) and has to be machined to closely match the shape of the cone to limit the risk of large stress concentrations. Adequate fillets and tolerances are taken into account.

The high-g Spring Starter system is a custom made winding spring system linked to the engine drive shaft. Located in the nose of the Propulsion Module, the spring is loaded by hand using the propeller before inserting the flyer in the shell. As the two blades sit in the lateral grooves of the cone when folded, the propeller cannot turn thus keeping the spring loaded as long as the flyer remains in the shell. As soon as the flyer is extracted from the shell by the parachute, the two propeller blades deploy out of their respective grooves and the spring starter unwinds starting the engine. Some in house experiments demonstrated repetitive successful starts using this technique.

5.2.4.2 Stress Analysis

The loads:

The rebound load is assumed to be axial. The step of the cone is therefore designed to take the 8kg overestimated weight of the entire flyer times 6,000 g’s (overestimated rebound acceleration).
*The results:*

Figure 5.18 is a COSMOS graphical stress analysis result of the Propulsion Module cone.

![Graphical Stress Analysis Of The Cone At Rebound](image)

*Figure 5.18: Graphical Stress Analysis Of The Cone At Rebound*

The stress level is under the yield strength of the 7075-T6 aluminum and the flyer should therefore be able to survive rebound. One risk however, is that one of the joints may fail due to the excitation force of the gun pressure wave if it hits one of the harmonics of the Internal Structure. No modal frequency studies or tests have yet been done.

**5.2.4.3 Experimental Testing**

The Propulsion Module high-g test has been delayed many times within the year. The spring starting mechanism has been successfully proven but the overall Propulsion Module high-g test still has to occur. Due to time constraints, the team agreed to test the Propulsion Module in the final Dahlgren test, in which the entire WASP system will be launched from a real gun. The final Dahlgren Test will be covered in the next chapter.
5.3 The Second Internal Structure Assembly

Bringing all the new designed parts together, the backbone of the WASP flyer can be assembled. Figure 5.19 is the WASP internal structure exploded view.

![Diagram](image)

**Figure 5.19: WASP New Internal Structure**

This assembly ends up the second WASP Internal Structure design.
CHAPTER 6

FINAL WASP ASSEMBLY, MISSION, AND TESTING

6.1 WASP Final Assembly

Each team had almost completed its own subsystem design and it was essential that all of the modules be brought together to verify possible interferences between them.

6.1.1 Assembly Details

The WASP can be in three states. It first starts completely folded in the shell. Then, at separation, the WASP flyer is extracted from the shell and remains attached to the Back End / parachute assembly. Finally, when the Back End is released, the flyer is in its deployed state.

6.1.1.1 The Flyer Within The Shell

The flyer starts entirely contained in the MK 48 MOD I shell and enclosed by the Back End on which are attached the SAL-GP ballistic fins.

Figure 6.1: The WASP Assembly At Launch
To survive rebound, it is essential that the flyer be tight, squeezed between the Back End and the front machined step in the shell. A slight preload is also preferred to reduce the impact of vibrations at rebound. Some theories claim that at least half of the set-back acceleration load has to be preloaded (Draper CMATD project). However, the team believes that adding a large preload simply adds additional stresses to the structure. Final adjustments were made to adjust the total length of the flyer to match the exact internal dimensions of the shell. According to design tolerances, the three modules stacked on top of each other to form the flyer add up to plus or minus 0.003 inch of the design length dimension. The shell was also machined to match the front part of the flyer. Since the shell had to be bored from its aft end using a long boring tool, the machinists could only guarantee a plus or minus 0.01 inch tolerance.

Tuning the length of the flyer is therefore done using ring metal shims between the Propulsion Module cone and the shell for a “too short” flyer or by accurately machining the cone step for a “too long” flyer. Figure 6.2 shows details of the WASP assembly at launch.

Figure 6.2: Detail Drawing of WASP Assembly At Launch
6.1.1.2 The WASP At Separation

When the metal collar retaining the Back End to the main shell is cut by the linear shaped charge, the deployed parachute pulls the Back End and the WASP flyer out of the shell. As mentioned previously, for stability reasons the fins remain attached to the flyer until the wings and all control surfaces have deployed. Figure 6.2 is a representation of the WASP flyer at separation. While the collar clamps are shown as two pieces in assembly, a circumferential split will occur when separation is initiated.

Figure 6.3: The WASP Flyer At Separation

The tails and the rudders deploy passively as soon as the flyer is extracted from the shell at transonic speeds. Only the wings are restrained to deploy until appropriate dynamic pressure is reached.
To activate the parachute deployment using the pyrotechnic pushers and the linear shaped charge to cut the collar, electrical wires need to be connected from the Back End to the computer electronic cavity in the Tail Module. When assembling these parts together using the explosive bolt, a connection is needed in the parachute cavity. Also, wires cannot support their own weight at launch, so they designed to pass through small drilled holes filled with epoxy to lock them in place.

6.1.1.3 The Deployed Flyer

The last WASP assembly configuration is when the parachute attached to the Back End is released by activating the explosive bolt. The wings and all other aerodynamic surfaces are deployed and the flyer is ready to start its mission. Figure 6.4 is a view of the deployed flyer after separation from the Back End to which the parachute is attached.

Figure 6.4: The Deployed Flyer
6.1.2 The Inertia Tensor

Using the CAD software on which most of the parts have been modeled, appropriate densities for each individual component was entered. Fuel, batteries and some electronics were taken into account but most of the bolts were omitted. However, since very few of them were used in the design, the total flyer assembly shown above in Figure 6.4 was considered a good approximation.

A total mass of about 15 lb (6.81 kg) was calculated. The Cg location was determined at 21.3 cm from the base instead of the required 20.6 cm. Final adjustment to remove adequate mass in the front can be done on the prototype. Also, with 80g of fuel, from full to empty tank, the flyer Cg excursion is only 2.54 mm which represents around 0.5% of the total length of the flyer. This value was acceptable for good handling qualities.

The new inertia tensor of the WASP flyer with all surfaces deployed is (in lbs In²):

\[
\begin{bmatrix}
139.22 & -0.91 & 4.97 \\
-0.91 & 409 & 5.38 \\
4.97 & 5.38 & 515.67
\end{bmatrix}
= \begin{bmatrix}
I_{xx} & I_{xy} & I_{xz} \\
I_{yx} & I_{yy} & I_{yz} \\
I_{zx} & I_{zy} & I_{zz}
\end{bmatrix}
\]

Using this inertia tensor, the flyer aerodynamic coefficients and power characteristics, the control team developed a complete flight simulation in collaboration with Draper Laboratory. This simulation\(^{(3)}\) was used to project the aerodynamic performance of the flyer using different control laws and gains. This flight simulation was extended with the complete ballistic flight and separation sequences.
6.2 WASP Mission

6.2.1 WASP Deployment Sequence

In Chapter 1, the WASP design from concept development to the final assembly was described. As shown, the goal was to transform a ballistic projectile into an efficient reconnaissance flyer and it was decided to do so adapting an existing illuminating projectile body. Every step from launch to complete deployment was revisited iteratively as more and more data, designs and analysis became available. From launch to full deployment, Figure 6.5 illustrates the WASP complete deployment sequences.

![Deployment Sequence Diagram]

**Figure 6.5: WASP Deployment Sequence**

First, the entire assembly is shot from a five inch Navy gun. As soon as it exits the barrel, the SAL-GP fins deploy (helped by the blast of the gun) for a fin stabilized ballistic flight. Forty seconds after launch (depending on the mission, gun elevation and target position), the Back End linear shaped charge is triggered, which cuts the steel collar linking the Back End with the main shell. At the same time, the two explosive bolt thrusters eject the parachute cover plate away from
the shell with 1000 lb of force. This cover plate pulls the parachute out of its compartment, allowing it to deploy and exert a 600 lb force on the Back End. The internal flyer, attached to the Back End by an explosive bolt, is extracted from the shell. Once separated from the shell, the flyer-Back End assembly is allowed to slow down for about 15 seconds, depending on the deployment altitude and mission. The propeller and the control effectors deploy and the engine starts. When a terminal velocity of 300 ft./s is attained, the wings deploy and the explosive bolt is activated 2 seconds later. The flyer is released and can start its mission

6.2.2 Reconnaissance Coverage

The simulation group worked on creating graphs that correlate launch angle, parachute opening altitude and range to reconnaissance coverage area of the flyer and camera definition(2). These graphs can be used to determine the deployment altitude and time at which the parachute should deploy (\(t_0\) being the gun initial acceleration) for different gun elevations. Some of these graphs can be found in Appendix I.

On those graphs, for specific gun elevation angles, different coverage areas are represented by rectangles. A camera pixel resolution is also associated to each coverage patch in function of the deployment altitude of the flyer. For a fix amount of camera pixels, the higher the flyer is, the lower would the image resolution be.

6.3 Dahlgren Eight Inch Canister Test

6.3.1 The Experimental Assembly

With the help of the Draper Laboratory machine shop, the MIT Central machine shop, the Aero/Astro and some additional external machine shops, piece by piece, the entire flyer was manufactured and assembled. All three modules, with all the parts, the two folding wings, the entire propulsion module and a modified MK 48 MOD 1 shell with a Back End were carefully machined to prepare for the Dahlgren Eight Inch Canister Test.
During the course of the year, the team had the chance to develop the prototype using the five inch Air Gun test facility at Picatinny Arsenal. As discussed previously, the five inch canister test imparts high g's, but does so for only 2 ms whereas a real gun acceleration lasts for 18 to 20 ms. What's more, other forces such as the rebound force and the possible excitation force resulting from the varying gun pressure wave can be destructive for an entire assembly.

One way to verify if the design can survive a real gun launch is to actually launch it from a real gun by having the entire assembly enclosed in a larger eight inch canister. This test can be performed at the Dahlgren, VA, Naval Surface Warfare Center (NSWC). This Navy base, located on the shores of the Potomac river, is essentially dedicated to Navy gun related experimental testing and naval warfare development. It has many Navy guns aligned on the shore, all pointing towards the Chesapeake bay.

The eight inch canister test has the following advantages:

1. The eight inch canister can contain the entire WASP assembly including the modified five inch Navy shell, but not including the fins.

2. Once launched from a Eight Inch Gun at high elevations, the canister with its payload is recoverable as a large parachute deploys and slows its descent into the river, not too far from shore. Once in the water, the retrieval is assured by a rescue team using boats and scuba divers.

3. The eight inch canister test offers nearly the same forces as a real five Inch Gun. If the design survives the eight inch canister test, there is a very high probability that it would survive a real five inch gun launch.

The eight inch canister test was especially effective because the flyer was recoverable. With a real five inch gun launch, the projectile would not be recoverable and a small electrical malfunction could for example prevent any separation from happening, therefore hiding any evidence of mechanical system and deployment mechanism diagnostics. As the Eight Inch Canister with its payload are recoverable, verification of mechanical and deployment mechanism integrity can be
done by hand, extracting the flyer from its shell once the entire assembly is removed from the canister.

The WASP assembly with its shell sits vertically in the canister as shown in Figure 6.6. A "fake" Back End is machined to be screwed to the canister using an ACME thread. The top part of the five inch shell is supported by the inside walls of the canister using a custom made adapter with large set-screws to adjust radially to the inner dimensions of the canister. This adapter allows vertical displacements of the assembly but limits cantilever moments at the base of the shell as the eight inch canister will tumble in the air prior parachute deployment (the canister has a slip ring obturator that prevents spin and there are no stabilizing tail fins attached to it).

![Figure 6.6: The Eight Inch Canister Experimental Setup Schematic](image)

Figures 6.7 and 6.8 show the entire folded and deployed WASP flyer and assembly respectively.
Figure 6.7: The Folded Flyer With Experimental Modified Shell and Back End

Figure 6.8: Author Holding The Deployed Flyer With Experimental Modified Shell and Back End
6.3.2 The Test

The Dahlgren test was initially scheduled for the end of April 1998. Since a stand alone test was too expensive, the team had to plan its test on the same day that another company was scheduled to use the Dahlgren experimental facility. In doing so, most of the up-front experimental setup cost would be absorbed by the company, thus reducing the team’s experiment cost. On May 14th 1998, Raytheon-Texas Instrument working on the Extended Range Guided Munition (ERGM) program and the team met at Dahlgren.

Figure 6.9 shows the eight inch canister in which the entire WASP assembly was installed.

![Figure 6.9: The Eight Inch Canister](image)

Figure 6.10 is the eight inch 54 caliber gun used to shoot the canister.

![Figure 6.10: The Eight Inch 54 Caliber Gun](image)
First, three slugs (fake shells) were shot in the morning of the 14th to calibrate the gun and to determine the exact amount of powder required. Then, at 4:37 PM, the WASP was shot with 12026 g's at 75 deg. of elevation reaching more than 7700 ft of altitude. After its recovery from the water, the canister was brought to a large disassembly area. Figure 6.11 shows the canister after its recovery.

![Figure 6.11: The Recovered Canister](image)

The entire shell was removed from the canister as shown in Figure 6.12. The collar, Back End and shell assembly showed absolutely no sign of failure and cracks!

![Figure 6.12: The After Launch Shell Assembly](image)
Finally, the two collars were removed and the Back End was pulled from the shell with the entire flyer attached to it. Absolutely no friction was observed. The two tails deployed perfectly and when completely out from the shell, the wings deployed as usual! Absolutely no cracks, no indents and no jamming mechanisms were observed! The WASP HGV prototype had successfully survived its high-g test! Figure 6.12 shows the successful WASP fully deployed after the launch.

![Image of WASP HGV Prototype](image)

**Figure 6.12: The Successful WASP HGV Prototype**

### 6.4 The FTV Test

The FTV is equipped with a larger engine than the one used in the HG but still does not have the necessary power to take off by itself. Because the operating velocity is 39 m/s, it needs to be launched from a moving vehicle that can reach at least this speed. Also, since it is hard to predict how the flyer is going to behave in flight, a high launch altitude is required to allow corrective maneuvers or parachute deployment in case of an emergency (a special parachute system has being developed for that purpose). The FTV will be launched from a remote-control ultra-light airplane at a minimum of 1200ft of altitude.

This thesis will not cover the FTV experimental testing since its first flight scheduled for the 26th of May 1998 is beyond this thesis due date.
CHAPTER 7

A WORD ON PROJECT MANAGEMENT

7.1 Team Organization

7.1.1 Work Assignment

Described in Section 1.5.1, the team was divided in different groups, each one responsible for the design, manufacturing and testing of individual subsystems.

The design groups really started to form in the middle of the summer 1997 as the WASP concept evolved and was broken down into different modules. Each individual team member took the responsibility of an individual subsystem according to personal interest and amount of work and research already invested.

In September 1997, additional graduate students joined the core team as some others were leaving for a total of nine engineers and two undergraduate students to bring the project to an end. The groups were than equalized in terms of the total amount of work, research and development effort each subsystem required. Common consensus about individual responsibilities were determined in team meetings.

7.1.2 Planning and Scheduling

The team scheduled its design work and experimental testing from June 1997 to May 1998 using a Gantt Chart.

In total, three schedules were available. Working back from the set deadline of May 1st 1998, a tentative main schedule listing the main tasks, design, assembly and testing dates was created.
Then, because the project relied heavily on experimental testing to validate the design, a separate detailed tentative experimental testing schedule was developed. This schedule covered all group’s experimental testing, that is: Wind Tunnel testing, Propeller and Propulsion testing, all Air Gun tests, the FTV test, other in house tests and the final Dahlgren test.

In addition to those two schedules, two week detailed schedules were presented at the weekly team meetings. These schedules covered essentially the detail design, manufacturing and planning work each individual team member was responsible for during that period.

Schedules were hard to design since all of the team members had courses, exams and different mandatory lectures to follow through the year. Very few members had the same classes and obligations and it was important to constantly update the schedules to accommodate each individual team member’s academic load.

As the project was reaching the middle of the mechanical design work in January 1998 where system integration became crucial, it was essential to have a very clear vision of the effect of each component on the overall project success in the event that this component design, manufacturing or testing date had to slip. A large four by three foot schedule was created on which all detailed design, system integration, manufacturing, and testing dates for each group of the HG and FTV vehicles were characterized. Direct critical paths were drawn on this large Gantt Chart so that the entire team could quickly refer to it and observe the implication of a postponed subsystem deadline.

7.2 Team Communication

7.2.1 Team meetings

Each week, the entire team reviewed and discussed project design work, experimental testing, planning and other miscellaneous project related topics.
During the concept development and design phases, a good part of the meetings were dedicated to design reviews as individual groups would present their work, generating numerous discussions around the table. Design meetings were also used to verify if all the groups were up to date and consistent with the schedule.

Often, when the team felt that the discussions were too critical, detail design involved, or when the group was not able to agree on a subject, smaller groups composed of topic-related key people, also called Tiger Team, would gather independently in smaller meetings during the rest of the week to tackle the problem in question. Agendas and resulting meeting minutes were sent to every member of the team including faculty and some Draper people using a common e-mail mailing list.

Finally, many additional mini-meetings were also necessary to supervise and coordinate the work of the different machine shops.

7.2.2 Work Environment

To improve on communication and efficiency, the team chose a large room for office base. Every member of the team had their respective desk and there were no walls for a resulting efficient communication between the team members. In addition, a large area was reserved for prototype assembly and another one for electronic testing and assembly. The office had a total of five computers including the Silicon Graphics workstation for solid modeling design and stress analysis.

7.3 Client Contact

As the team was designing the vehicle, it was required to update the team's client Draper Laboratory upper management. As mentioned in the introduction, this project was the starting point of the MIT / Draper Partnership and since Draper was providing resources, they played an important role, both as a customer and contributor to the project.
CHAPTER 8

CONCLUSIONS

Over a two year period, a group of graduate students and their advisors developed an unprecedented cannon-launched reconnaissance vehicle prototype. There is still much to do before the WASP system can become operational. More tests are required to verify separation and proper deployment of the parachute, wings and control surfaces at transonic and operational speed respectively.

8.1 New Ideas

The two HGV and FTV prototypes are very useful first development vehicles but as the team researched and developed specialized skills in the high-g field for the last two years, it can now look back on the first design steps and comment on its work.

Clearly, improvements are possible. For example, the entire internal structure was conceived from the Tail Module to the Propulsion Module and the flyer overall weight could certainly be reduced as more nearly optimum structural design and component placement could be achieved. For that purpose, Mr. Thierry Casiez and myself initiated the design of an optimization program that can minimize weight of the flyer. Ideally, this program would take into account the flyer Cg position linked to all aerodynamic forces and moments, cross sectional basic rules of stress analysis and all required components size and volume that have to fit within the constrained volume of the shell (wings, tail, fuel tank, engine, batteries and all electronics). The approach uses Genetic Algorithm to first optimize for component placement, later adding the other constraints if the first step demonstrates success.

Also, the folding high-g wing design can be improved so that it is more efficient to manufacture. The critical design items in the wing design are the hinges, around which the individual wing sections pivot. If redesigned using a different hinge geometry, the wings could be cast using cast-
ing alloy instead of being machined out of cold rolled 7075-T6 aluminum, and still be strong enough to survive the 15,000 g’s. Casting the wings would reduce their manufacturing cost by a factor of 10 for large production volumes.

Also, once the machined HGV prototype was assembled, it became clear that small backlash in the gearing system and small fuel tank assembly problems should be rectified. Redesign of those parts would enhance the quality of the overall product.

8.2 Project Spin-off's

Through the WASP design and development process, the team was able to develop to develop significant understanding of the high-g environment. With the help of numerous Air Gun tests, the team discovered that some inexpensive slightly modified off-the-shelf actuators and small cameras can survive the required 15,000 g’s. Similarly, the team also developed on a high-g propulsion unit, using an inexpensive two stroke engine assisted, which can be started using a simple starting mechanism. Finally, the team also created modular design and proven compact high-g folding wing system that can be scaled up and used in other applications.

Currently, one of the trends in the United States has been to develop fast response, inexpensive cannon-launched smart munitions. Companies like Raytheon-Texas Instruments are still developing an Extended Range Guided Munition (ERGM). Others like SAIC, have obtained support from the U.S Navy to develop an Advanced Technology Demonstration (ATD) vehicle in their case called FASM. This FASM vehicle is a very long low-g cannon-launch flyer that eventually would be used to carry munitions and different sensors such as cameras and radars. Still in there concept design stage, they plan to use an inflatable wing technology to deploy the wings after launch. Since the WASP team has already developed compact foldable high-g wings, SAIC showed an interest in the design and would consider certain members of the WASP team to design a suitable version of the wings for them. A proposal has been addressed and future possible negotiations will tell whether the MIT/Draper partnership wins the contract or not.
Also, the team had the chance to present the project to the Office of Naval Research (ONR) in Washington. The group of people attending the meeting are directly responsible for the initiation of new U.S Navy projects and money allocation of the latter. Among the ATD projects chosen each fiscal year, resources are set aside to help small private businesses to develop innovative systems that could be used by the Navy. These funds are called SBIR funds that stands for Small Business Innovative Research. After the meeting, the U.S Navy expressed a strong desire to develop an extended length and extended range WASP that would be used to carry a radar payload to locate targets at more than 35 nautical miles from the launch site (normally a ship). A preliminary WASP II shown in Figure 8.1 was dimensioned and scaled to carry the required 2.5 lb radar payload.

Figure 8.1: The WASP II

Clearly, there could be interesting work down the road. With this WASP project, the WASP team members have developed expertise that some organizations could effectively use. The Draper entrepreneurial objective has been satisfied.
8.3 Project Summary

In two years, a group of graduate students and their advisors designed an unprecedented cannon-launched reconnaissance vehicle and two prototypes were manufactured to prove the concept. The high-g prototype was successful as it demonstrated full mechanical integrity after a 12,000 g launch from an eight inch gun. Results from the second prototype built to demonstrate the stability augmented flying qualities of the concept are still pending. Additional experimental testing such as wind tunnel and explosive / separation testing are required to further verify all aspects of the concept. This work should be supported for the upcoming summer of 1998.

The WASP project technical challenge was extraordinary and it took creativity, hard work and passion to develop and manufacture the two prototypes. This project was also a real team experience as each individual learned how to accept his or her team mates’ different approaches, opinions and design judgments.

The first project of the MIT/Draper Partnership has been declared successful, beyond expectations. A new project has been approved starting in July 1998. This project should push the technical challenge even further, aiming once again for “unobtainium”.
References


(9) Personal Notes, Torrey Radcliffe
## Operational Vehicle Component List

### Known Components

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<th>Component Name</th>
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### Unknown Components

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**Wide Area Surveillance Vehicle**
Appendix B2: Operational Vehicle Signal Flow Diagram
Appendix C: Concept layouts
Appendix E1: Internal Vision Sketch
Appendix E2: First Assembly Hand Drawing
Appendix F: Tail-Pivot Brainstorming
Appendix G: Air Gun Test Accelerometer Readings

Tall Module Shot #1: 4041 Peak g's measured.
Tail Module Shot #2: 16078.3 Peak g's measured.

11:18:34 2/20/98

Channel: Recorder 0
Y1: 242.916245 G
T1: -0.0733 s
dt: 0.0005 s
dY: 15835.422623
Min: 242.916245
Int: 4.100918

Y2: 16078.338667 G
T2: -0.0728 s
dY/dt: 31.671606
Max: 16078.338667
RMS: 9741.503838
Tail Module Shot #3: 16489.35 Peak g’s measured.
Appendix H: Pressure Wave Comparison

Examples - High "G" Profiles

Diagram Air Guns
155mm Gun
Rail Gun

Acceleration (g's)

Time (msec) - Setback Only

Acceleration (g's)

Diagram Air Guns
155mm Gun
Rail Gun

Acceleration (g's)
Appendix I: WASP Area Coverage

12 min powered flight
numbers indicate: dep at 11, sensor res. II

surveillance after travel to 15 nmi

immediate surveillance
Flyer Flight Profile, Gun Launch plus Surveillance Area, 35 deg Launch Elev

12min powered flight

numbers indicate: depl alt (ft), sensor res (ft)

immediate surveillance

surveillance after travel to 15 nmi