Cooperative Parent Child Unmanned Aerial Vehicles: A Systems Engineering Approach

By

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Submitted to the Department of Aeronautics and Astronautics in partial fulfillment of the requirements for the degree of
MASTER OF ENGINEERING
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
May, 1999
[June 1999]

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Abstract

The MIT/Draper Technology Development Partnership Project was initiated and sponsored by Charles Stark Draper Laboratory, Inc. (CSDL) to give students an opportunity to design, develop and validate a first-of-a-kind high technology system. This program addresses projects that meet one of the important national needs and the organizational requirements of CSDL. In addition, it aims to foster a sense of entrepreneurship in the students.

This thesis reviews the first year of work completed on the Parent Child Unmanned Aerial Vehicle (PCUAV) project. Various potential applications for this system have been identified. A systems view is used throughout, describing the top-level trades that were made to develop a concept that would meet a broad range of user's needs. Chronological descriptions of the project and system concepts are treated in this thesis.

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Acknowledgments

I am grateful to Prof. John J. Deyst and Charles W. Boppe for encouraging and guiding me at every moment to do my best. I thank them for giving me the unique opportunity to lead the student-team and for giving me the freedom to take the initiative and play an important role in making decisions.

I would like to thank our sponsors at Draper Laboratory. Brent Appleby and Richard Martorana had been very valuable to this project in defining its goals and objectives and providing valuable inputs from the market and CSDL's perspective.

Prof. John Chapin, Col. Peter Young, Prof. Carlos Cesnik and Prof. Mark Spearing were always available for consultations and guidance. Their feedback during the weekly meetings is greatly appreciated.

I would like to thank my teammates, Sanghyuk Park, Alexander Omelchenko, Tarek S. Nochahrli, Alan Chhabra, Aaron Rogers, Jacob Markish, Michael Parkins and Andrew Heafitz for the wonderful experience that we shared as a team on this project.

Finally, I would like to thank my parents who have encouraged me in all my endeavors.

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List of Acronyms

CAMMS	Cooperative Aggregate Mission Management System
CDR	Concept Design Review
COTS	Commercial Off The Shelf
CSDL	Charles Stark Draper Laboratory
DARPA	Defense Advanced Projects Agency
DoD	Department of Defense
GPS	Global Positioning System
GS	Ground Station
LOS	Line of Sight
MAV	Micro Aerial Vehicle
MEMS	Micro Electro Mechanical System
MOUT	Mission Operations in Urban Terrain
MUAV	Micro Unmanned Aerial Vehicle
NRL	Naval Research Laboratory
NRT	Non Real Time
NBC	Nuclear Biological Chemical (Warfare Agents)
PCUAV	Parent Child Unmanned Aerial Vehicle
QFD	Quality Function Deployment
RF	Radio Frequency
RT	Real Time
SATCOM	Satellite Communication
SOF	Special Operations Forces
TUAV	Tactical Unmanned Aerial Vehicle
UAV	Unmanned Aerial Vehicle
UCAV	Unmanned Combat Aerial Vehicle
WLAN	Wireless Local Area Network

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CHAPTER 1

Introduction

1.1 Background of the MIT/DRAPER Technology Development Partnership

The Technology Development Partnership program between the Massachusetts Institute of Technology and Charles Stark Draper Laboratory (CSDL) was initiated in 1996. This program supports two-year projects that aim to address an important national need and some organizational requirements of CSDL. It provides the students with an opportunity to design, develop, and demonstrate technologies for new product concepts. In addition, the program helps the students to develop entrepreneurial skills.

A project was launched in July, 1998 with a goal to design, develop and test key technology elements of a parent and child unmanned aerial vehicle system concept. The first year of work consisted mainly of assessing the market needs and developing systems and vehicle concepts. The second year of work will involve the detailed design, manufacturing and testing of a prototype. This thesis describes the first year of effort on the "Parent Child Unmanned Aerial Vehicle, " also known as the PCUAV project.

1.2 PCUAV Project Objectives

Several goals were established at the beginning of the project. The primary objectives were to meet an important national need and to satisfy some of the organizational needs of Draper Laboratory. In addition, it was required that the concept be a challenging, first-of-a kind system containing some new and challenging technical elements which are characterized as "unobtainia." The design process should involve an integrated, multi-disciplinary approach that would account for cost, functionality and performance benefits of the proposed system; when compared to existing assets that might be used for the same purpose. The first year team was responsible for identifying the customer needs, deriving technology drivers, and developing concepts. Unobtainia were identified and preliminary design of the system was initiated. The second year team will be responsible for the detailed design of the demonstration system, its construction, and testing.

1.2.1 National need

Many modern day needs require information gathering of various kinds, involving a broad array of operational scenarios. Often these scenarios are driven by mission needs and the kind of information that must be gathered. A wide range of sensor types may have to be deployed, sometimes with precision and stealth. Mini and micro unmanned aerial vehicles are some of the kinds of systems that are under consideration by officials at the Defense Advanced Research Projects Agency (DARPA) and the Office of Naval Research (ONR) as candidates to fulfill important needs. These small vehicles have a number of positive attributes but they are limited in their range of operations and endurance by their communication transmission power and fuel capacity. These limitations can be mitigated if small-unmanned aerial vehicles (UAVs) are complemented by a relatively larger parent vehicle. The parent would carry smaller UAVs, deploy them at a destination, coordinate their operations, and relay information to and from the ground station user. The use of multiple UAVs results in a system-of-systems concept whose flexibility provides an ability to perform a range of diverse missions. In addition, these missions can be sustained by continuous replenishment of the child systems at the site of action.

1.2.2 Draper Laboratory Needs

The Charles Stark Draper Laboratory has designed and/or developed systems for a wide range of vehicle types including aircraft, launch vehicles, ground rovers, submersibles, rotorcraft and projectiles. A moderate-scale fixed wing parent aircraft, as described above, would complement CSDL's repertoire of vehicle types. In addition, this vehicle would provide CSDL with an opportunity to leverage its existing core competencies in mission planning, guidance, navigation, and control technologies.

1.2.3 Demonstrations

The project would conclude with demonstrations of key technologies that are necessary for development of an operational system. This would validate the unobtainia identified. Lessons learned from the demonstrations should serve to show that the concept is feasible and can proceed to prototype development. Fig 1.1 shows a projected sequence of events that would lead to operational deployment of PCUAV by the end user.

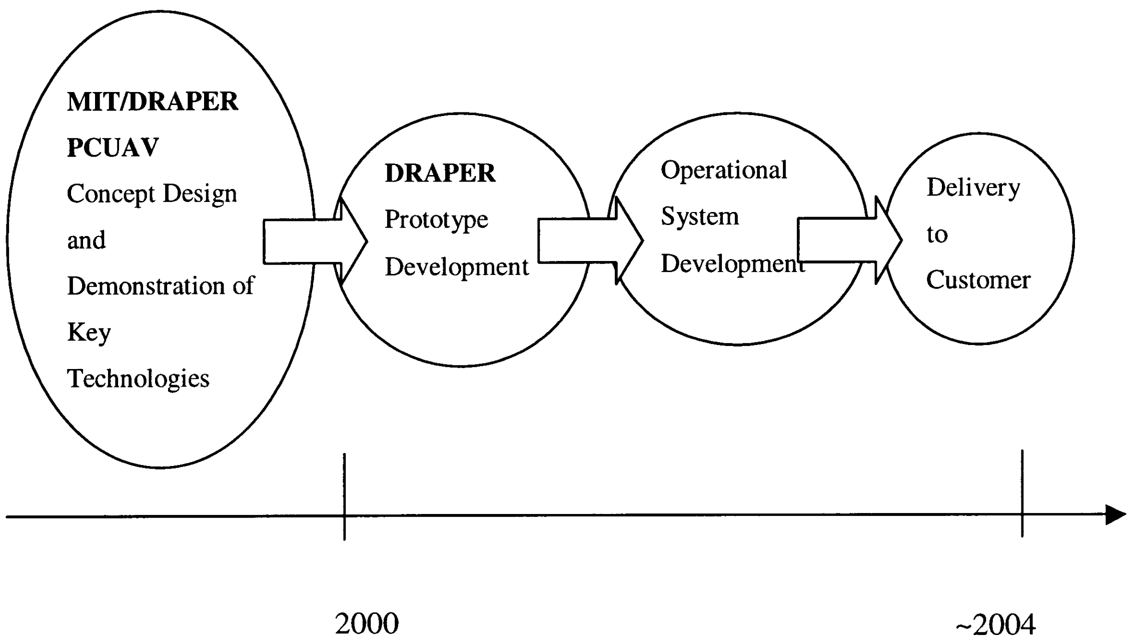


Fig 1.1 Evolution of PCUAV

1.2 Thesis Objectives and Outline

The primary goal of this thesis is to describe the work completed by the first year team and to provide details, rational, and technical highlights of the chosen concept. The description is chronological and addresses the various phases of the first year of effort.

Fig 1.1 shows how the PCUAV concept might evolve into an operational system over the next few years. Under the MIT/DRAPER partnership program, the concept would be designed, developed and key technologies will be demonstrated. After demonstrating the feasibility of essential technologies/approaches at MIT, a prototype would be developed followed by an operational system. The entire development cycle of PCUAV spans five to six years. During this period, several supporting technologies might evolve and these will need to be anticipated and taken into account while developing the concept. In addition, the needs of the end users have to be identified to set the requirements for this system.

Chapter 2 describes the market, customers, and their needs as derived from numerous interviews and literature searches. Customer needs and technical requirements that flow from these needs are prioritized. Chapter 3 describes the various concepts that were explored, the downselected concept, and presents a detailed functional analysis of the chosen system concept. Chapter 4 describes the risks involved in the development of the chosen system concept and the approaches taken to mitigate them. Chapter 5 describes the author's experience as student project manager. Chapter 6 concludes the thesis with project status, recommendations and conclusions.

CHAPTER 2

Needs Assessment and Requirements Analysis

2.1 UAV Market Assessment

Unmanned aerial vehicles (UAVs) have been used as early as WW II. In Southeast Asia UAVs flew missions considered too hazardous for manned aircraft, performing photography, real-time TV relay, electronic intelligence and battle damage assessments. Typically, UAV missions were conducted at a fraction of the cost incurred using manned aircraft and at significantly reduced risk to human operators. The significant impact of UAVs in military operations, however, was not apparent until the Gulf War. The U.S military has identified an urgent need for the integration of UAVs in both strategic and tactical units.

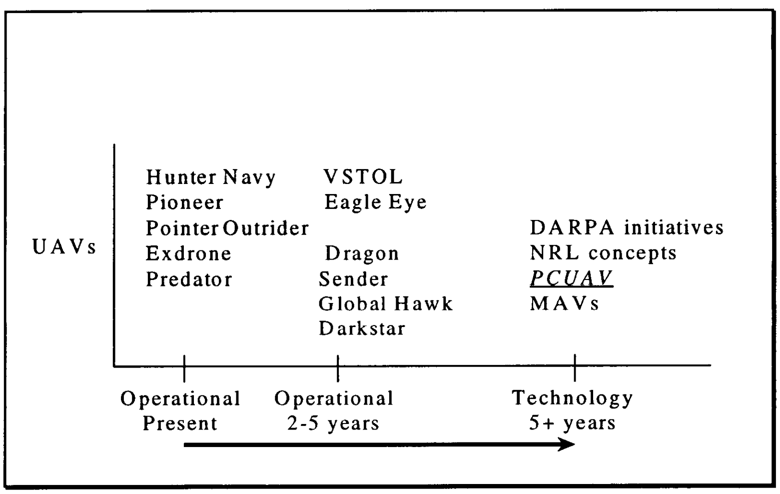
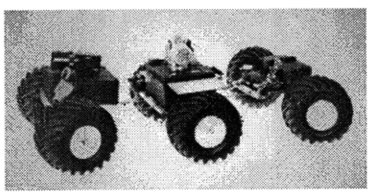


Fig 2.1 PCUAV system and other UAV programs

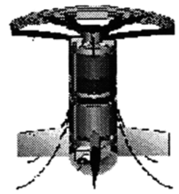
Fig 2.1 shows the timeline for various projected UAV programs. The PCUAV is envisioned as a system that might be operational by about 2004. The market for UAVs is still in its early stages of development and is likely to experience significant growth over the next 10 years. The current worldwide UAV market is about $2 billion a year and is expected to grow at 12% per annum through 2005. This comprises just the military air-vehicle segment, which makes up only 15% of the overall market consisting of UAVs and supporting equipment. The PCUAV system has the potential to capture a significant fraction of the market because of its unique features and capabilities.

2.2 Customers and Application Scenarios

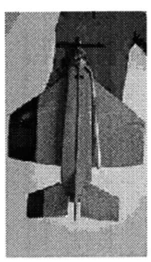
Many defense, commercial and scientific research applications have been identified for potential uses of the PCAUV system. These include armed forces, law enforcement agencies, TV news services, traffic management and hazard assistance.



DRAPER Ground Robot



DRAPER/Lutronix MAV



IAI MUAV

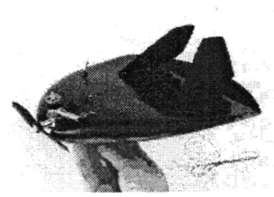


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Fig 2.2 Potential micro systems as PCUAV child systems

The primary purpose of PCUAV system is to deploy modest capability assets where they are needed at a distance from the user. These assets include mini and micro systems that may be used for sensing, targeting, and communications, and may eventually find application as weapons, as well. Many potential micro systems have been identified. These include ground sensors, miniature robots and micro aerial vehicles with a maximum dimention of about 6" in any direction. Fig 2.2 shows some of the micro systems, currently under development, that might be used as child systems in PCUAV. They include the CSDL/Lutronix hovering MAV and a few other projects sponsored by DARPA. These projects are expected to mature by the year 2000 or later and hence cannot be effectively integrated into the PCUAV project today. Mini systems are significantly larger and include small aircraft with a span of up to 4 ft.

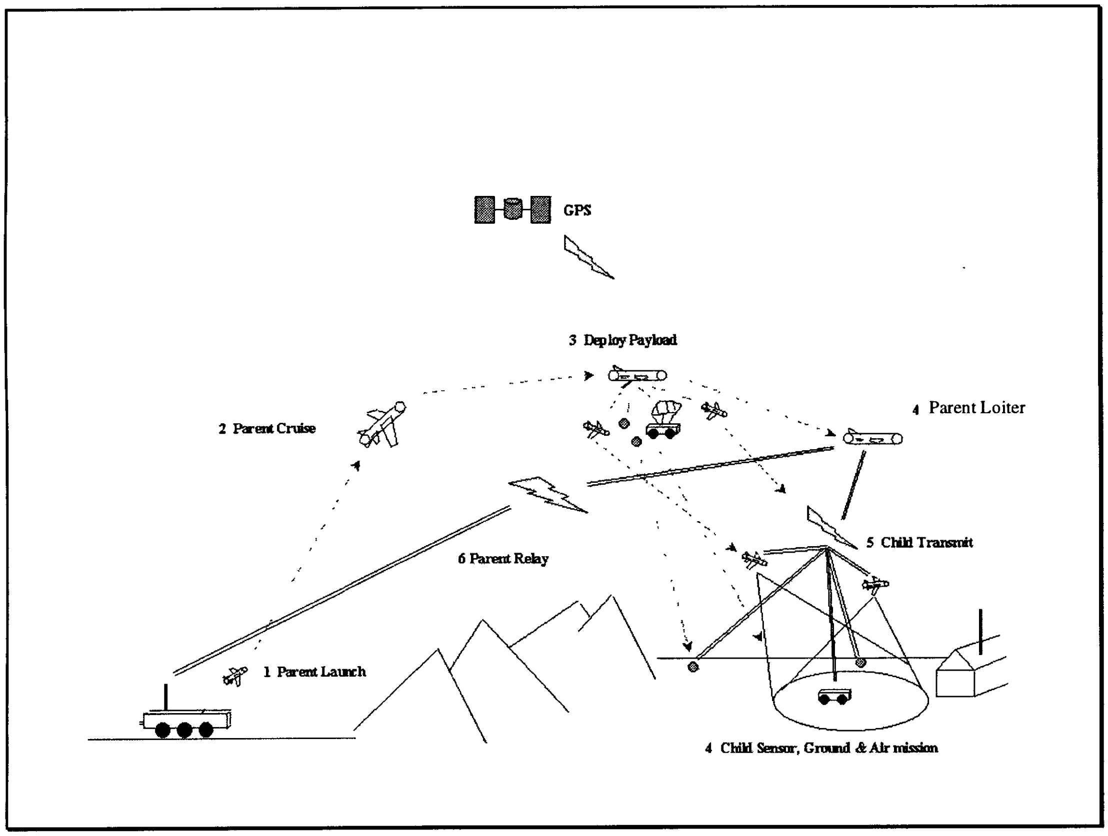

Fig 2.3 PCUAV and a typical mission scenario

Multiple mini/micro systems might be deployed from the same parent as shown in Fig 2.3. Hence, a number of missions might be accomplished with the PCUAV system. A mission can be changed while it is being executed and the most relevant sensors, mini or micro systems can be deployed when necessary. In addition, when a mini/micro system is exhausted, a new one could be deployed from the same parent to maintain sustained presence and continuation of the mission. In addition, a new parent can replace the previous one, thus further extending the mission. Hence, the flexibility that is provided by the parent child system-of-systems concept might be effectively utilized in many ways not previously available to users.

DARPA has been identified as the primary customer for this project, as the objectives of the project matched closely with their needs. DARPA encourages the design and development of innovative, advanced defense systems utilizing state-of-the-art technologies. One of the goals of this project is to initiate an effort that has high potential to be funded for further development. However, DARPA is not the ultimate customer. The armed forces (i.e., the Air Force, Navy, and Army) use the products developed under DARPA contracts. Hence, the team studied their needs to get a better understanding of real requirements. A few application scenarios have been identified for the PCUAV system. These potential scenarios were used in discussions with the officials at defense organizations to refine the needs and to stimulate new ideas. In addition, a few civilian and scientific research applications were also identified.

While DARPA's needs are motivated primarily by cutting edge technologies, the end user needs are strongly driven by ease of use, compatibility with existing infrastructure and cost. Important end user needs include a high degree of autonomy, portable lightweight hardware, short take off and landing, and compatible fuel.

A number of application scenarios have been identified for military missions. While many existing UAVs meet the requirements of the military services in the near term, a few scenarios have been identified where the parent-child concept can execute novel missions, which can only be executed by the PCUAV system. The following section describes some of the mission requirements.

2.2.1 Nuclear Biological Chemical (NBC) Warfare Agent Detection

Detection of NBC warfare agents requires that sensors be placed within the contaminated region. Some of the challenges include sensor deployment at less than 40 ft. in attitude. Most of the current UAVs fly at much higher altitudes. In addition, they are designed to carry specific payloads that may not include sensors for NBC detection.

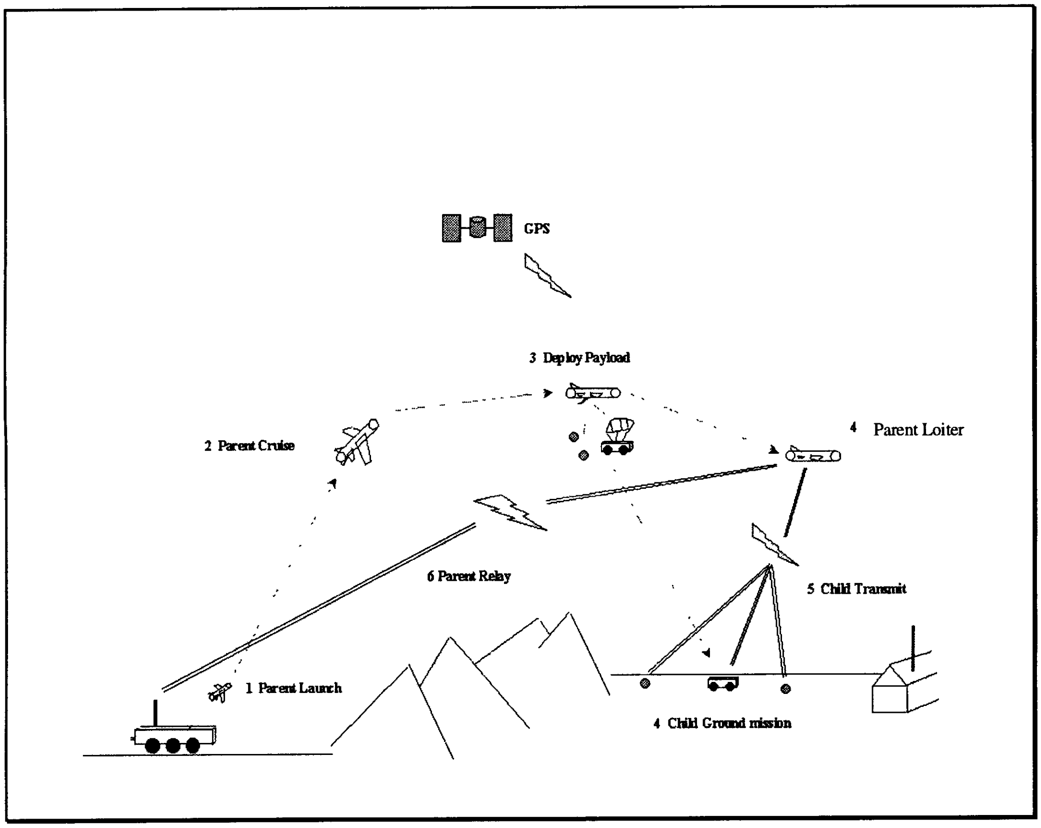

Fig 2.4 Ground vehicle and sensor deployment for NBC detection

The PCUAV system can be effective in this scenario. A few commercial off-the-shelf MEMS based biological and chemical sensors are available today. These can be integrated with mini or micro systems. Each of the child UAVs or ground robots can carry different sensors. In an operational scenario, a parent aircraft flies over the region of interest and sends images to a ground station. The user identifies the potentially contaminated areas where sensors need to be deployed. On getting the user command, the parent deploys child systems carrying the most suitable sensors to the designated areas. Fig 2.4 shows the deployment of ground vehicles, carrying NBC sensors, from the parent.

The parent then serves as a communication relay and provides command and control to the ground vehicles.

2.2.2 Mission Operations in Urban Terrain

It has been cited that most modern day warfare will take place in cities [9]. In 1993, 18 US soldiers from an elite-fighting unit died on the streets of Mogadishu, Somalia. Russian troops have died on the streets of Grozny, capital of Chechnya. These developments have shown that armies in defensive postures often take shelter in cities and convert the battle into unconventional guerrilla warfare. While the troops of modern armies have been trained to fight in open battlefields, even the most advanced and well-equipped army finds it difficult to operate and win in an urban situation. Difficulties arise due to ruined streets and buildings that limit mobility, large numbers of non-combatants that limit the use of fire support, and tall building structures that affect the ability to communicate.

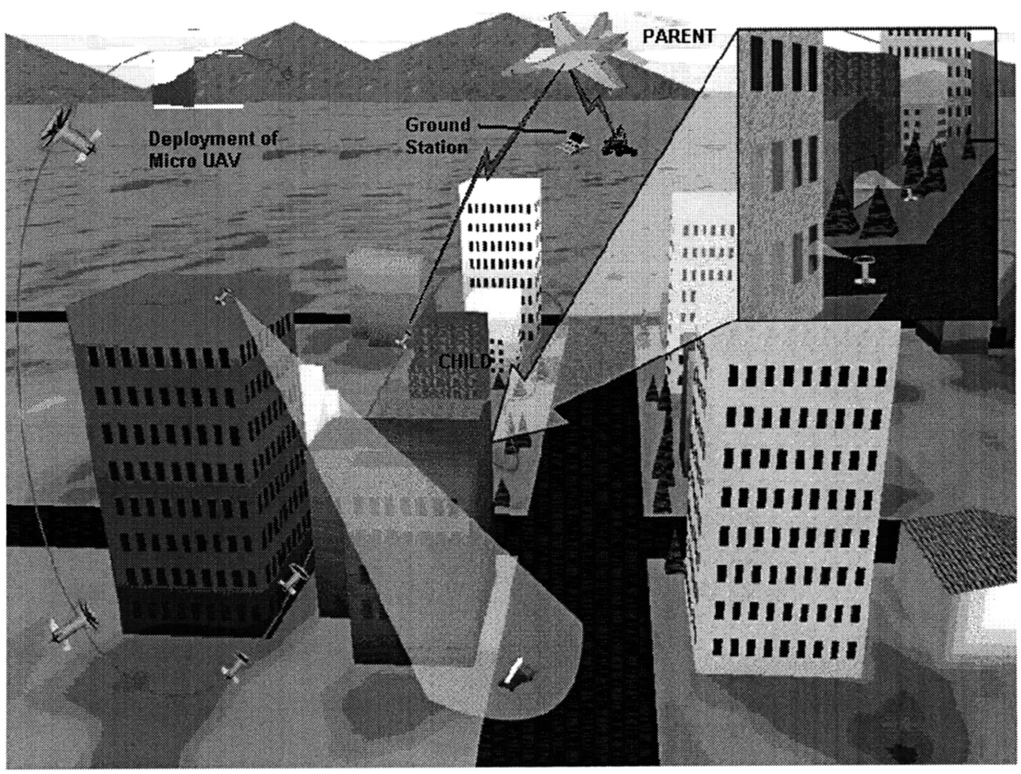

Fig 2.5 A typical PCUAV application for MOUT

Fig 2.5 shows the PCUAV system making use of a DRAPER MAV for operations in an urban environment. The PCUAV system would deploy micro UAVs inside such cities and provide information about activities that would otherwise be obscured by buildings and other structures. Before storming the city, the PCUAV system would provide vital information to troops stationed outside the city. Such information is difficult to obtain with the current UAV systems because of their size and maneuverability constraints. When army operations take place in the city, real-time information can help the commanders to make appropriate decisions.

2.2.3 Bomb Damage Assessment

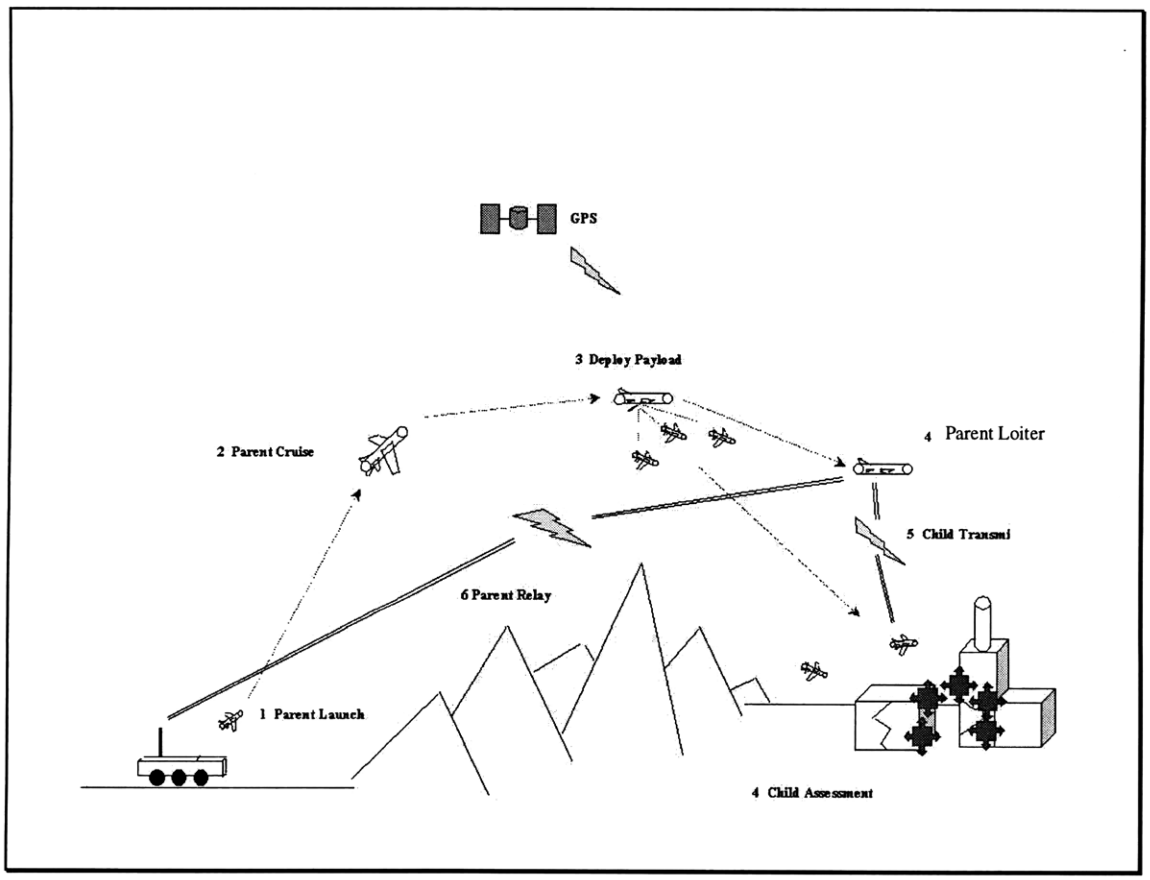

Fig 2.6 PCUAV applied for bomb damage assessment

Assessment of damage caused by artillery shells or air raids can be achieved by close range reconnaissance. While conventional UAVs are prone to ground fire, the PCUAV system can be effectively employed to get an accurate estimate of the damage by fusing the images from multiple angles to generate 3-D images of the target. With these 3-D images, untargeted/undamaged areas can be accurately geo-located and retargeted. Fig 2.6 shows a typical application scenario with the mini/micro systems sensing images of the targets from various angles to generate 3-D images.

2.2.4 Naval Application

Advantages of having multiple distributed systems include sensing from various locations simultaneously. For example, Fig 2.7 shows a ship launched PCUAV system deploying sonar buoys from a parent in order to locate enemy submarines.

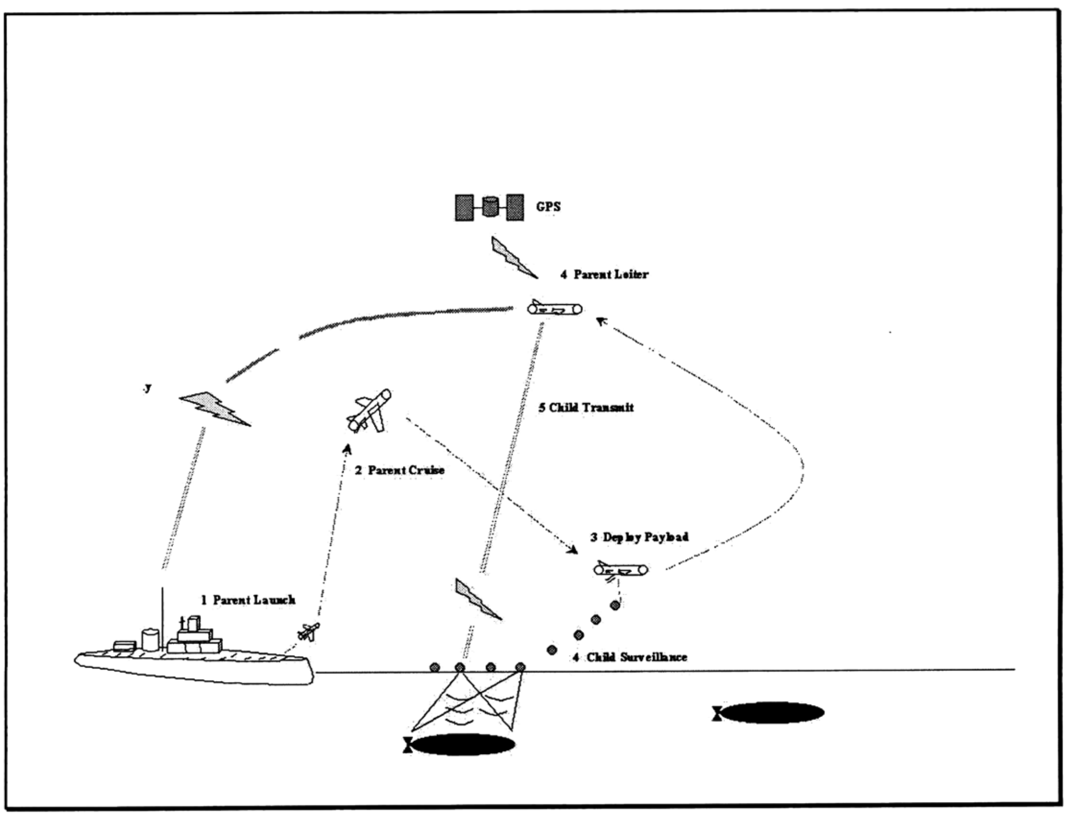

Fig 2.7 PCUAV locating submarines by triangulation

2.2.5 Radar Jamming

Micro and mini aircraft may be useful for jamming radars at close range. The power required to jam a radar is inversely proportional to the square of the distance to the radar. Micros that can closely approach the radar receiver can be very effective in jamming the radar compared to conventional systems, which must operate from longer ranges. Preliminary studies indicate that only 1W of power is required to effectively jam a radar at a range of 2km or less. As shown in Fig 2.8 the micro/mini system can be envisioned to be deployed close to the enemy receiver. Because of their small size, the micro/mini systems can be operational for only a short duration of time before they run out of power. The parent UAV could then replace them by deploying a new set of micro/mini systems.

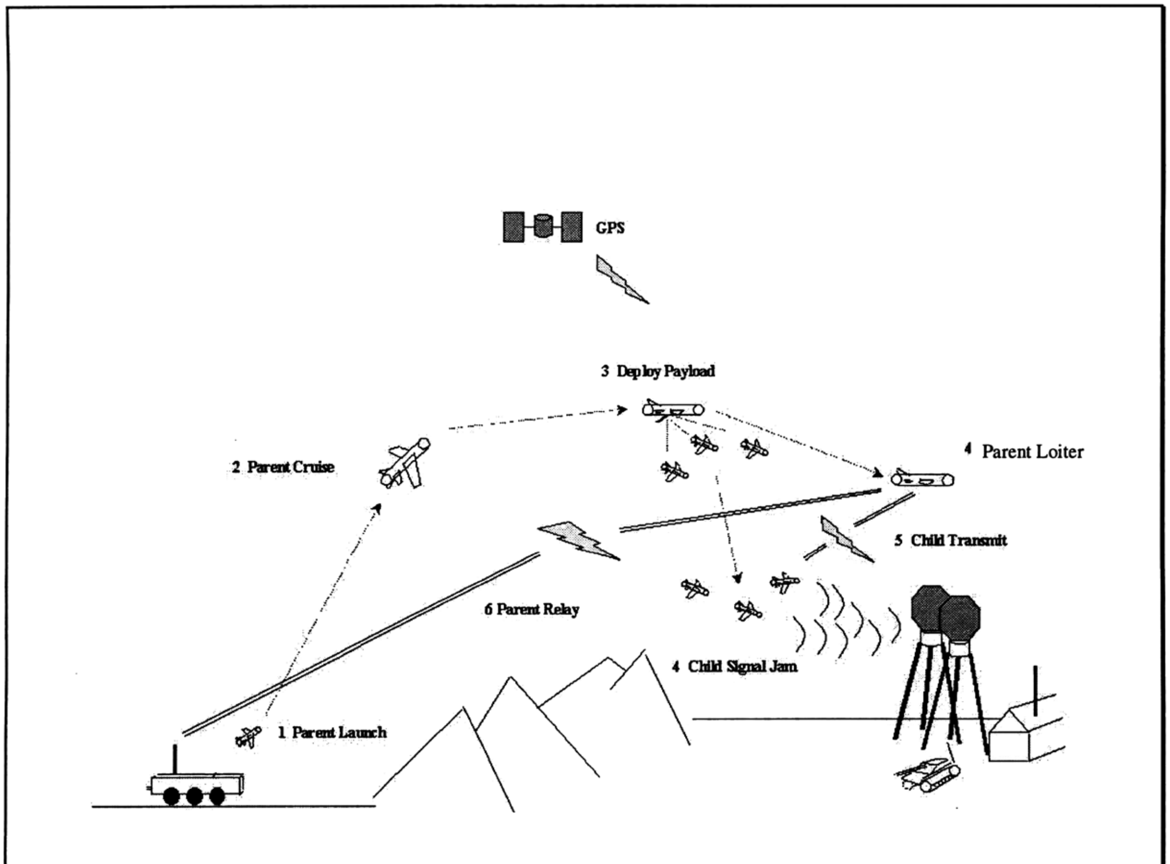

Fig 2.8 Radar jamming using PCUAV system

2.2.6 Scientific Research Applications

Certain scientific applications, such as studies of atmospheric phenomenon like hurricanes and tornadoes, require sampling of data simultaneously from distributed locations. A parent would fly close to regions of interest and deploy sensors or micro UAVs close to such phenomena. Specially designed micro UAVs might fly further into locations where data needs to be sampled while the parent stays at a safer distance. The micros would transmit their locations and sensor data to the parent. The parent would collect such information from micro systems and transmit it to the ground station for further analysis. Such atmospheric phenomena are not predictable. A PCUAV could fly to a location where they are detected or chase a moving tornado. Hence, PCUAV may enable research that is difficult or impossible with existing systems. Relatively low flight velocities of parent and children may limit this application.

2.2.7 Other Applications

The PCUAV system might also be used for drug interdiction, wildlife and forest inspection, border patrol and other non-military needs. These applications require searching over large regions to detect events of interest. Most of the events of interest are transient in nature and hence require the sensors to be placed at the right location and at the right time.

PCUAV can perform a collaborative search. The parent and child systems could simultaneously search different parts of a region of interest. The parent would collect images from child UAVs and transmit them to the ground station. The search pattern can be repeated to detect changes over time. Fig 2.9 shows typical collaborative search patterns by parent and child UAVs over a region of interest.

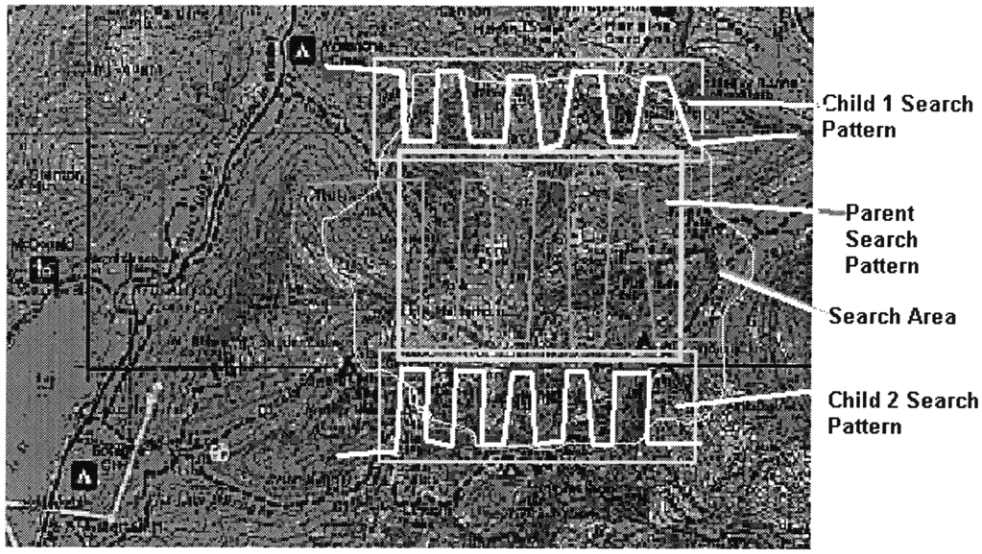

Fig 2.9 Collaborative search by PCUAV

In the near future, some space-based applications like interferometry using distributed satellites, can use PCUAV system-of-systems concepts. An experiment on similar lines is being conducted at Stanford University. The project, called OPAL, consists of a parent satellite that would deploy smaller nanosatellites.

2.3 Requirements Analysis

A number of potential PCUAV missions were identified in the previous section. All of these missions can be executed by the PCUAV concept due to the flexibility offered by its system-of-systems nature. In order to define the PCUAV system in more detail, it is necessary to identify the system requirements that would satisfy most of the customer needs.

2.3.1 Customer Requirements

Table 2.1 was developed to prioritize the original customer requirements. These requirements and their priority ranking were generated by the team upon discussions with members of the operational community. A high score of nine was assigned when the requirement was strongly desired by the customer. A low score of three was assigned when the requirement was not very important to the customer.

Customers were prioritized based on their assumed relative importance to this project. This is shown by the numbers in the second column. A higher score was assigned to the more important customer, 100 being the highest possible score. These numbers were obtained from the market survey, interviews with potential end-uses and objectives of the project. DARPA was assigned the highest score of 100 as it was felt that the objectives of the project, described in Chapter 1, matched closely with their needs.

The priority ranking of each customer need (score 9-5-3) was weighted by the relative importance of the customer to the project (column 2), the results were tallied, and a total score for the customer requirement was generated. The total scores of all customer requirements were compared and ranked (last row of Table 2.1).

The most important customer need turned out to be ease of use of the system. This meant that relatively inexperienced users should be capable of operating the system with very little training. In addition, the system should have some degree of autonomy. The other highest scoring customer requirement was compatibility of fuel and communications systems for efficient integration with existing facilities. Heavy fuel is used by the Army and Navy. Use of any other fuel by the PCUAV would require additional support equipment and would increase logistical complexity. One of the main reasons for the failure of the Outrider program has been cited to be its inability to operate with heavy fuel.

		Customer Needs															
		Relative Importance of Custom	Easy to Use	Compatible fuel (safe hanling)	Day/Night Capability	All weather Operations	Low Cost of Ownership	Low Objective Location Error	Low Mission Cycle Time	Spectrum of collection Capabilities	Portable	Long Endurance	Short T/O	Long Range	Large Area Coverage	Short Landing	Interoperatebility	Long Life of System
Customers/Market Segment	DARPA	100	9	9	9	9	9	9	9	9	9	9	5	9	9	5	9	3
	ARMY	90	9	9	9	9	9	9	9	9	9	5	9	5	5	5	5	5
	NAVY	50	9	9	9	9	9	9	9	9	5	9	9	9	9	9	3	5
	SOF	60	9	9	9	9	5	9	9	5	9	5	9	5	3	5	3	3
	MOUT**	30	9	9	9	9	9	9	9	3	9	5	9	3	3	9	3	3
	FBI/Police	10	9	9	9	5	9	9	3	5	5	5	5	5	5	5	3	5
	Road Traffic	20	9	9	9	9	9	3	3	3	3	9	3	5	5	3	3	5
	News Media	10	9	9	9	9	9	5	5	5	3	5	5	5	3	5	3	5
	Hazard Assistance	10	9	9	9	9	9	5	9	5	3	5	3	5	3	3	3	5
	Emergency/ Crisis/Nuclear	5	9	9	9	9	5	5	9	9	3	9	3	5	3	3	3	3
	Border Patrol	10	9	9	9	9	9	9	5	5	3	9	3	9	9	3	5	9
	Environmental Protection	5	9	9	3	5	9	3	3	9	3	3	3	5	3	3	3	5
	Meteorology	5	9	9	5	9	9	3	3	9	3	9	3	9	9	3	3	5
	Presidential Protection	5	9	9	9	9	5	9	3	5	9	9	9	3	3	5	3	3
			3690	3690	3640	3630	3410	3410	3340	2970	3060	2820	2880	2640	2460	2260	2030	1690
			10	10	9.864	9.84	9.24	9.24	9.05	8.05	8.29	7.64	7.8	7.15	6.67	6.12	5.5	4.58
	Ranking		1	1	2	2	3	4	5	6	7	8	9	10	11	12	13	14

Table 2.1 Prioritizing customer needs

Customer Needs	Relative Importance of Cust Needs	Integrated vehicle design	Efficient Aerodynamic/Control Design	Multiple sensor data fusion	Autonomous Guidance, Navigation and Control	Stable Platform	Expert Mission Planning	Rugged / Robust	Night Sensor Technology	Efficient Data Collection and Processing	High Lift Capability	Low specific fuel consumption	Light Weight Structure	Child Vehicle Management and Control	Versatile Sensors	Acccurate sensors/algorithms
Easy to Use	10	5	0	5	9	3	9	9	9	9	3	0	0	9	3	9
Compatible fuel (safe handling)	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Day/Night Capability	9.9	5	0	5	9	0	0	0	9	0	0	0	0	0	5	3
All weather Operations	9 8	0	9	5	9	9	5	9	0	0	0	0	0	0	9	3
Low Cost of Ownership	9 2	0	9	0	0	0	0	9	0	5	0	9	5	0	0	0
Low Objective Location Error	9 2	0	0	9	0	9	9	0	5	9	0	0	0	9	0	9
Low Mission Cycle Time	9 1	3	0	0	3	0	5	0	0	0	0	0	0	0	0	0
Spectrum of collection Capabilities	8	9	0	9	0	0	0	0	5	0	0	0	0	0	9	0
Portable	8 3	5	0	0	0	0	0	0	0	0	0	0	5	0	0	0
Long Endurance	7 6	3	9	0	0	5	0	0	0	0	9	9	5	0	0	0
Short T/O	7 8	9	5	0	0	0	0	0	0	0	9	0	5	0	0	0
Long Range	7 2	5	5	0	0	5	0	0	0	0	5	9	5	0	0	0
Large Area Coverage	6.7	0	3	5	0	0	3	0	0	5	5	5	3	9	0	0
Short Landing	6 1	0	5	0	0	0	0	0	0	0	3	0	6	0	0	0
Interoperatability	5 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Long Life of System	4 6	5	0	0	3	3	0	5	0	0	0	0	0	3	0	0
Rating Index		10	9	9	8	7	7	7	7	6	7	6	6	6	6	6

Customer Needs	High Fuel Capacity	Weather resistant hardare protection (rain,heat	S-VTOL	High Reliability	Maintainable	Adaptable to multiple missions	Modular Design	Advanced Targeting System	Easy Setup	Collision Avoidance	Multiple communication Capability	High rate data links	High System Redundancy	Long life of critical components
Easy to Use	0	3	3	5	9	5	5	9	9	9	5	5	9	0
Compatible fuel (safe handling)	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Day/Night Capability	0	0	0	3	0	0	0	0	0	0	0	0	0	0
All weather Operations	3	9	0	3	0	0	0	0	0	0	0	0	5	0
Low Cost of Ownership	0	0	0	0	9	5	0	0	3	0	0	0	0	9
Low Objective Location Error	0	0	0	0	0	0	0	9	0	3	0	5	0	0
Low Mission Cycle Time	0	0	0	5	0	3	9	0	3	0	0	9	0	0
Spectrum of collection Capabilities	0	0	0	0	0	3	0	0	0	0	3	3	0	0
Portable	0	0	0	0	0	0	9	0	3	0	0	0	0	0
Long Endurance	9	3	0	3	0	0	0	0	0	0	3	0	5	5
Short T/O	0	0	9	0	0	0	0	0	0	3	0	0	0	0
Long Range	9	0	0	3	0	0	0	0	0	0	5	0	0	0
Large Area Coverage	9	0	0	0	0	0	0	0	0	3	0		0	0
Short Landing	0	0	9	0	0	0	0	0	0	0	0	0	0	0
Interoperatability	0	0	0	0	0	9	0	0	0	0	5	0	0	0
Long Life of System	0	9	0	0	5	0	0	0	3	5	0	0	5	9
Rating Index	6	5	4	5	5	5	5	4	5	5	4	5	5	4

Customer Needs	Short/Simple Training	User Friendly Interface	Extensive use of COTS	Fuel Based Propulsion System	Ground Sensor Precision Landing	Supportable and Maintainable Software	Open System Architecture	High Manuverability	High Thrust-to-Weight	Self Diagnostics, Fault Identification and Isolatio	Compact Design (to fit in suitcase)	DFMA	Authoritative control response	Large onboard data storage capacity **
Easy to Use	9	9	0	0	9	5	5	9	3	9	3	0	9	3
Compatible fuel (safe handling)	0	5	0	0	0	0	0	0	0	0	0	0	0	0
Day/Night Capability	0	0	0	0	0	0	0	0	0	0	0	0	0	0
All weather Operations	0	3	0	0	0	0	0	3	0	0	0	0	0	0
Low Cost of Ownership	3	0	9	5	0	5	3	0	0	0	0	9	0	0
Low Objective Location Error	0	0	0	0	0	0	0	0	0	0	0	0	0	9
Low Mission Cycle Time	0	0	0	0	0	0	0	3	0	0	0	0	0	0
Spectrum of collection Capabilities	0	0	0	0	0	0	0	0	0	0	0	0	0	9
Portable	0	5	0	0	0	0	0	0	0	0	9	0	0	0
Long Endurance	0	0	0	9	0	0	0	0	0	0	0	0	0	0
Short T/O	0	0	0	0	0	0	0	0	9	0	3	0	0	0
Long Range	0	0	0	0	0	0	0	0	3	0	0	0	0	0
Large Area Coverage	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Short Landing	0	0	0	0	9	0	0	0	0	0	3	0	0	0
Interoperatability	3	3	0	0	0	5	3	0	0	0	0	0	0	0
Long Life of System	3	0	5	0	0	5	5	0	0	9	0	0	0	0
Rating Index	4	4	3	3	4	4	3	4	3	3	4	2	2	5

Effects Greatly	9
Effects Moderately	5
Effects Mildly	3
No Effect	0

Table 2.2 QFD relationship matrix relating customer needs to technical requirements

2.3.2 Technical Requirements

Having ranked the customer requirements, several technical approaches/ requirements for each customer requirement were derived. In addition, a preliminary functional flow analysis was performed to identify the basic functional requirements of the PCUAV system (e.g., communication between multiple systems). Technical requirements/approaches to perform these functions were also obtained. As each technical requirement was developed, its influence on each of the customer requirements was noted in the QFD matrix as shown in Table 4.2. A high score of nine was given when the technical requirement strongly influenced the customer need; five for moderate influence; three for mild influence and zero for no influence.

The relative importance of each customer requirement, derived from the previous QFD matrix, is shown in column 2. The score for each technical requirement was tallied and a total score was generated. The total scores of all technical requirements were compared and ranked. Integrated parent-child vehicle design turned out to be the most important technical approach. This is a novel approach conceived by the author. In this approach, the parent is integrated with a relatively large child system (mini UAV). Some of the subsystems of the mini aircraft are used to augment the parent's capabilities while the mini is integrated with the parent. Thus, the mini aircraft would contribute to the performance of the parent. The next chapter discusses this approach in detail. Because of its relatively large size, the mini aircraft, as compared to the micros, can carry more capable payload sensors enabling a spectrum of sensor data collection capabilities. Because this approach is new and different, it is a kind of unobtainium and satisfies one of the primary objectives of the project.

2.4 Competition

The concept of a parent system assisting a child system has been witnessed both in terms of aircraft launching other aircraft and on Apollo missions. Solicitations requesting proposals for a parent-child UAV system have been put forth by government agencies. These developments and the following show that potential competition exists for the PCUAV system.

2.4.1 CAMMS

The Northrop Grumman Corporation has successfully demonstrated the autonomous control of four unmanned aerial vehicles by a single operator using the Cooperative Aggregate Mission Management System (CAMMS)[10]. The flight demonstration was conducted on July 25, 1998 at the Naval Weapons Test Center, China Lake, Calif. CAMMS software performed detailed mission planning and assigned each vehicle specific flight profiles to cooperatively execute tasks. Potential applications of CAMMS include unmanned combat air vehicle concepts (UCAV). All the aircraft involved in this test were large UAVs which took-off separately and landed separately. Although the other details of the flight test were not available, it is presumed that this project has the potential to compete with the PCUAV system.

2.4.2 Sender

Sender is a lightweight, low-cost, small UAV developed by the Naval Research Laboratory (NRL). This portable system with four foot wingspan has a one way range of 100 miles. These features make it very attractive for low cost missions. The Sender, however, has some limitations. It has a very high wing loading requiring a sophisticated launch mechanism. It also has limited loiter capability and small payload capacity and its communication system cannot transmit high bandwidth data. However, miniaturization of electronic systems can significantly enhance the capabilities of this system. Fig 2.10 shows a Sender UAV and some of its features.

- Electric Drone
- Portable-Packed in suitcase
- Speed: 50 - 90 kts
- One Way Range: 100 miles
- Payload: 2.5 lb
- Wingspan: 4 ft
- Endurance: 2 hrs

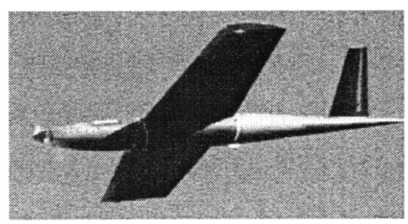

Fig 2.10 Sender UAV

CHAPTER 3

Concept and Architecture Development

Three different PCUAV concepts and their operational system architectures were considered and compared against each other, in terms of performance and functional capabilities, for a given common mission. Because of the diverse nature of the concepts, the mission was not specified in detail but was broadly defined as follows:

1. The system should execute a mission at a distance of 100 km from the point of launch.
2. The mission duration at the point of interest should be 20 minutes.
3. The system (or the most valuable parts of it) should return to the point of launch

   Fig 3.1 shows a typical mission profile of a PCUAV concept.

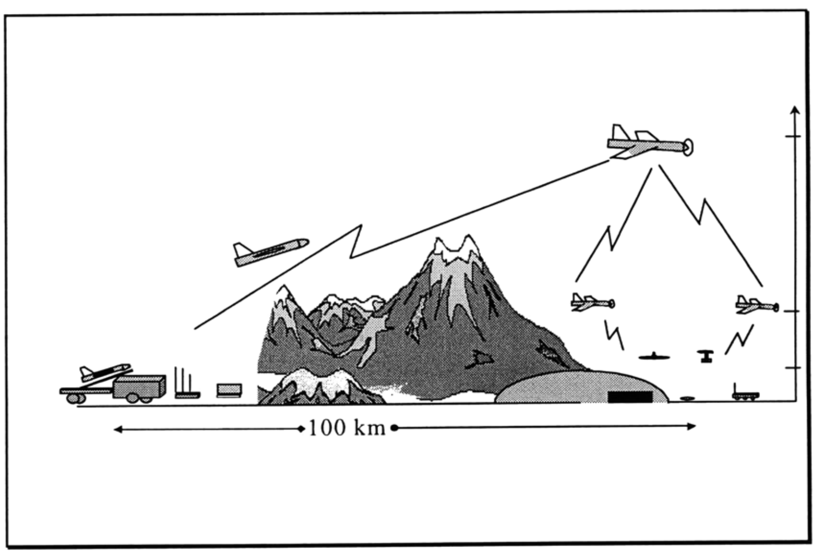

Fig 3.1 Mission for comparing concepts

The team formed three groups to investigate the three system concepts listed below

1. Multiple Independent Aircraft
2. Integrated Parent Child Concept
3. Micro Systems Cargo Transport

Each of the concepts had its own advantages and disadvantages. To gain better insight, the concepts were further developed to meet the objectives of the mission and the customer needs identified in the previous chapter.

3.1 Concept I: Multiple Independent Aircraft

This concept consists of multiple independent aircraft that would take-off and land separately. These are relatively small vehicles of about 5.5kg take-off weight with a payload capacity of about 400g.

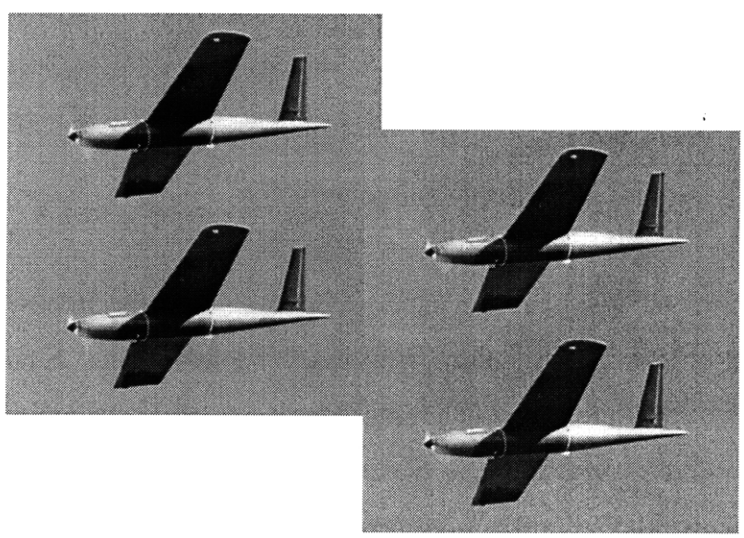

Fig 3.2 Multiple independent UAVs

This concept does not involve challenges in terms of vehicle design as aircraft of this size are in the current inventory. However, many system challenges need to be addressed. Each of the aircraft must be capable of operating independently. While executing a mission one of the aircraft can assume the role of a parent. This concept was investigated to get a better understanding of existing systems that can be used as PCUAV without the deployment and retrieval features.

3.1.1 Advantages of Multiple Independent Aircraft

System Redundancy: Unlike the other Parent-Child concepts, this concept does not have a single point failure. In the case of loss of one aircraft, another aircraft can replace it and the mission could continue uninterrupted. Hence, the probability of mission success is higher for this concept.

Indefinite Time over Target Area: The vehicles at the target can be continuously replaced with new aircraft and the mission could be sustained over an indefinite period.

Formation Flight to Destination: The aircraft can fly in a V- formation (like a flock of migratory birds) and hence reduce the induced drag on some of them, thus increasing range and endurance.

3.1.2 Disadvantages of Multiple Independent Aircraft

Many separate vehicles must be supported. All the aircraft must take-off and land independently. Use of a large number of independent vehicles increases the complexity in the logistics of operations and handling. Because the aircraft are relative large compared to micro systems, they are less maneuverable and can be more easily detected and targeted. Hence, the system is not capable of executing all of the missions identified in the previous chapter, such as operations in an urban environment.

3.2 Concept II: Integrated Parent-Child

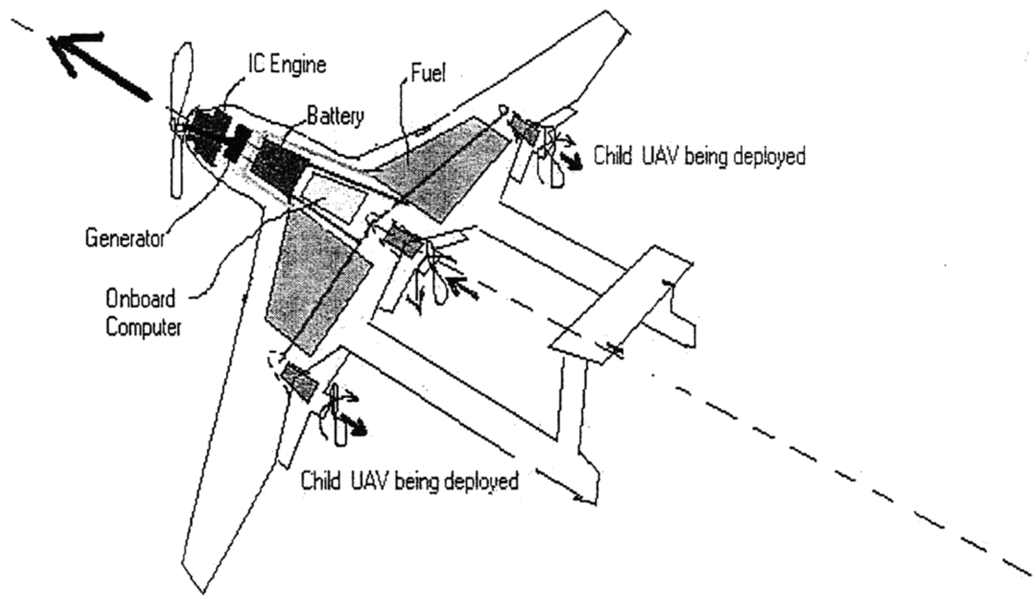

Fig 3.3 Integrated parent-child concept

The integrated parent-child concept, shown in Fig 3.3, explores the possibility that the parent might be integrated with the children to obtain simplicity and cost reduction for the total system. The children are relatively large compared to micro systems. Their sensing and communication capabilities are comparable to the parent UAV. However, they are smaller and have much less range and endurance. Also, the children are integrated with the parent in a manner so that they can contribute to the parent's performance rather than simply act as payload during cruise and/or loiter.

3.2.1 Advantages of Integrated Parent-Child

The child UAV's engines produce thrust during take-off and cruise. The additional thrust significantly reduces the take-off distance required by the parent. Since the engines are started at take-off, problems related to remote-start of piston engines are avoided. In addition, the response time of the system is reduced because the parent can travel faster to the mission site. The parent-child configuration can be optimized to provide a net aerodynamic advantage to the integrated system and hence increase range and/or endurance. While the child UAV is integrated with the parent, its sensors might be utilized. Thus, for example, a child UAV's camera can be used by the parent.

3.2.2 Disadvantages of Integrated Parent-Child

Because of the novelty of this concept most of the systems involved in the integration need to be developed. Instabilities may occur during deployment and/or recovery. Since the child UAVs are relatively large in size, the parent can carry only a few of them. Also, many of the missions mentioned in the previous section cannot be accomplished because of the large size of the child UAVs. Aerodynamic properties of the parent are altered after deployment. So, the parent needs to be designed for stable operations with two or more different aerodynamic configurations. Separation and deployment mechanisms will increase complexity.

3.3 Concept III: Micro System Cargo Transport

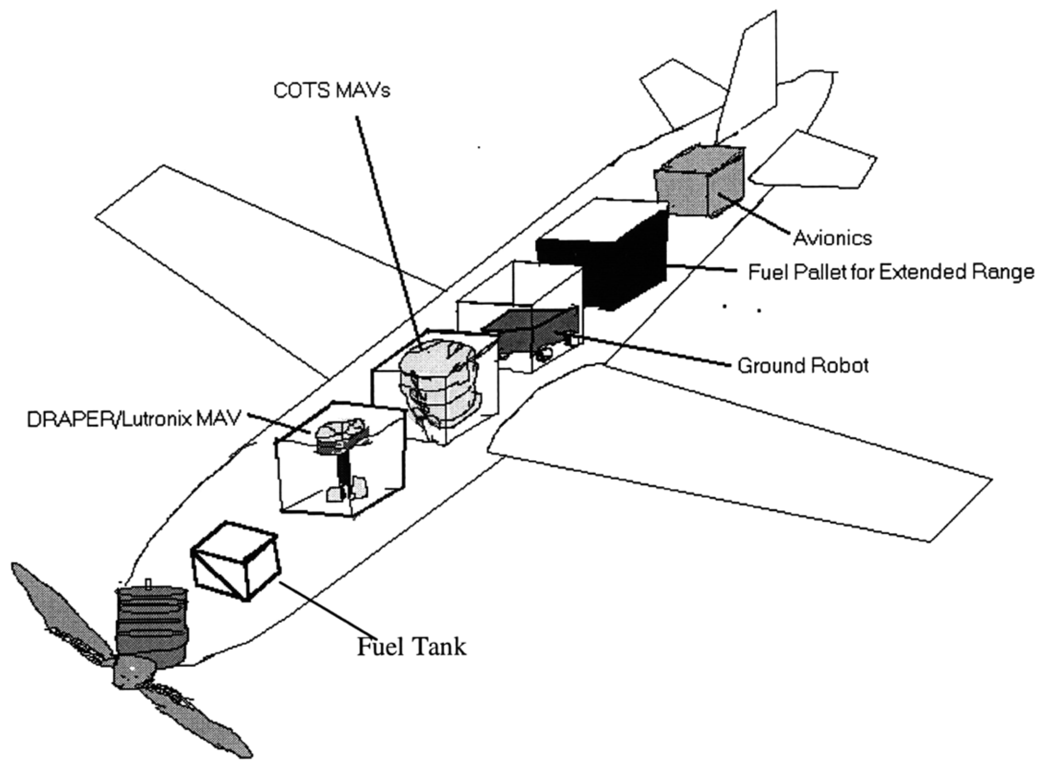

Fig 3.4 Micro system cargo transport

Concept III is envisioned as a bus for micro UAVs. A number of micro systems have been identified as potential child systems. Some of them are shown in Fig 2.2. Concept III enhances the performance and capabilities of these systems by carrying them to the destination, deploying them, and coordinating their activities. Since a wide range of micro systems are likely to be available in the future, it is proposed that they be packaged into a standard PCUAV pallet that can be dispensed by the parent. Standard PCUAV pallets have an internal dimension of 6" so that they can carry most of the proposed micro UAVs. Fig 3.4 shows a parent aircraft carrying four pallets; the first contains a Draper/Lutronix hovering MAV; the second contains a stack of fixed wing MAVs; the third contains a ground robot; and the fourth contains fuel for extended range.

3.3.1 Advantages of Micro System Cargo Transport

A wide range of systems can be delivered to the destination. Most of the missions mentioned in the previous chapter can be executed by this concept. One or more of the cargo pallets can be replaced with a fuel pallet to increase the range or endurance.

3.3.2 Disadvantages of Micro System Cargo Transport

Because of the small range of communications of the micro systems (about 600m – 1000m) the parent has to fly close to them and hence is vulnerable in hazardous situations.

3.4 Downselection of Preferred Concept

Characteristic	Weighting	Arch I	Arch II	Arch III	Arch I'	Arch II'	Arch III'
Multimission	10	3	4	5	30	40	50
Unobtainium	10	3	4	5	30	40	50
Reusability	8	5	3	4	40	24	32
Gather Info/Payload Cap	8	3	4	5	24	32	40
Reliability (Mission Execution)	8	5	3	2	40	24	16
Short T/O and Landing	8	3	4	3	24	32	24
Portability	7	2	4	4	14	28	28
Feasibility	5	5	4	3	25	20	15
Covert/Stealth	5	2	3	5	10	15	25
All Weather	4	5	4	3	20	16	12
Cost	4	1	2	3	4	8	12
Maintenance (Refuel-charge)	3	4	4	4	12	12	12
					273	291	316
					MAX	400	

Table 3.1 Comparison of concepts and downselection

The three concepts that were explored had many advantages as well as disadvantages. A common set of characteristics, shown in the first column of Table 3.1, was identified. These characteristics include the ability to execute a wide range of missions (multimission), challenges involved in developing the concept (unobtania) and other features that would satisfy customers needs (Short T/O and Landing, Portability etc.). The characteristics were ranked according to their relative importance to the project (column 2). The concepts were given a priority ranking on a scale of 1-5 depending on how well they demonstrated these characteristics. The ranking figures were supported by results from preliminary design calculations of the three concepts for the mission identified in Fig 3.1. The score for each concept was tallied and a total score was generated. These scores were compared and it was found that there was no clear winner because the concepts fared very well relative to each other. Instead of choosing the best concept, the team decided to incorporate the most interesting features of all the concepts and generate a new concept that would be explored further. This resulted in a concept consisting of a fleet of vehicles of the type shown in Fig 3.5.

3.5 Concept IV : Integrated Parent/Mini/Micro System

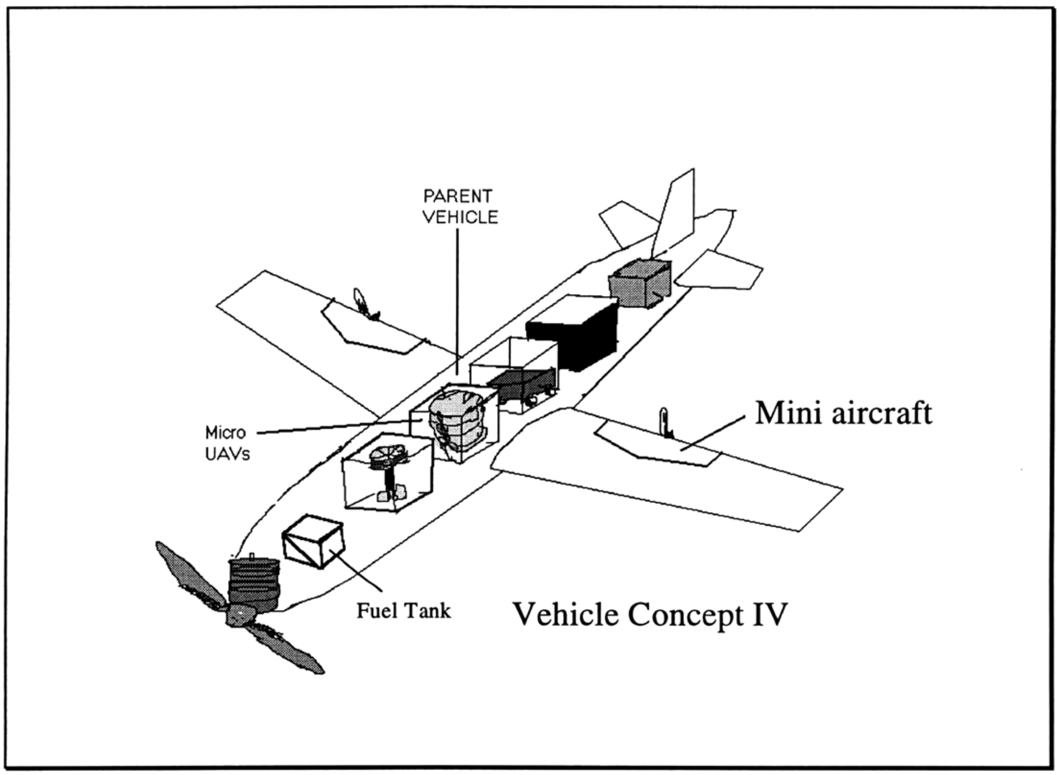

Fig 3.5 Selected vehicle concept

Concept IV incorporates the various features of the previous three concepts while attempting to overcome their disadvantages. The parent carries two sets of child systems - mini UAVs on the wing and micro systems in the fuselage. Mini UAVs are small aircraft as in Concept I. Micro systems are packaged in pallets as in Concept III. The system would take-off on a rail and/or with rocket assist to give it a short take-off capability. Parachute landing is proposed for retrieving the parent and the mini.

Fig 3.6 shows the concept operation in a three layered architecture. The least valuable of the assets is closest to the ground, while the more valuable ones are at higher altitudes. While mini UAVs fly at about 1 km from the surface, the parent flies at about 2-3 km above the ground. Micro systems are either on the ground or fly very close to it. Since the micro systems are limited in their range of communications, the mini UAVs act as relays between the micro systems and the parent. However the parent has a stronger transmitter and can transmit commands directly to the micro systems, and also provides communication with the ground station.

Though the architecture is complex, the flexibility provided by the availability of a fleet of systems, in layers, with various capabilities, makes this concept applicable to all the missions discussed in the previous chapter.

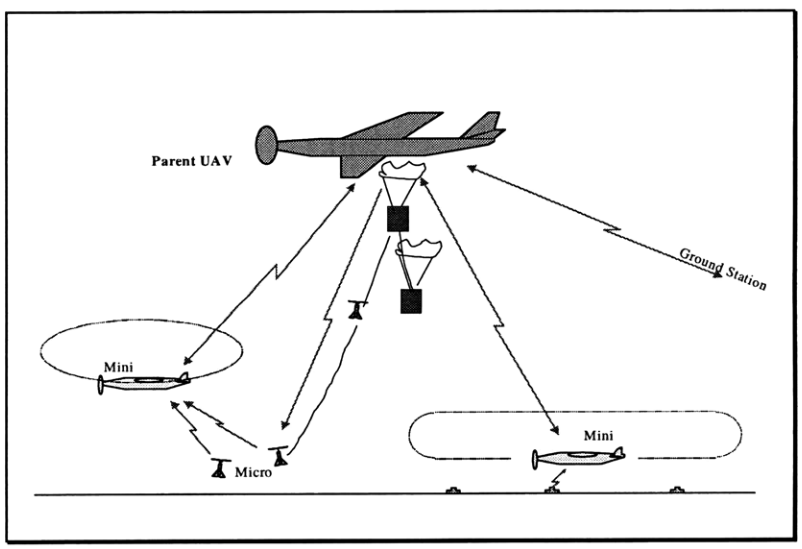

Fig 3.6 Three layer architecture of concept IV

3.5.1 Roles of the Vehicles

The following are the roles of the different vehicles involved in Concept IV.

Parent UAV

1. Carries and deploys the mini and the micro systems at the mission site.
2. Coordinates the mission by sending commands to the deployed systems
3. Communicates with the ground station (either directly or through another UAV like Predator)
4. Carries a sensor suite of its own (e.g., camera, radar, IR) and gathers information on its own.
5. Other functions envisioned for the parent include refueling and retrieving the mini UAVs.

Mini UAVs

1. Carry their own mission payloads
2. Act as a communication relays between the micros and the parent
3. Deploy miniature ground sensors with precision
4. Collect data from miniature ground sensors
5. Help the parent in multisensor surveillance
6. While integrated to the parent at take-off and cruise:
    a) Provide additional thrust to the parent
    b) Provide aerodynamic advantage to the parent
    c) Provide an array of sensor capabilities to the parent

Micro UAVs, Sensors, Robots, Ground Sensors

1. Carry various sensor packages for executing a wide range of missions
2. Transmit the sensor information to the mini UAVs

Fig 3.7 shows the PCUAV in both its strategic and tactical roles. The system is being designed for two-man-portable tactical Forward Line of Troops (FLOT) applications. It can also be modified to be carried under the wing of a Global Hawk class UAV and dropped at destinations much further away from the point of launch. In its strategic role, a PCUAV can communicate with a larger UAV or a satellite to transmit information to the ground station.

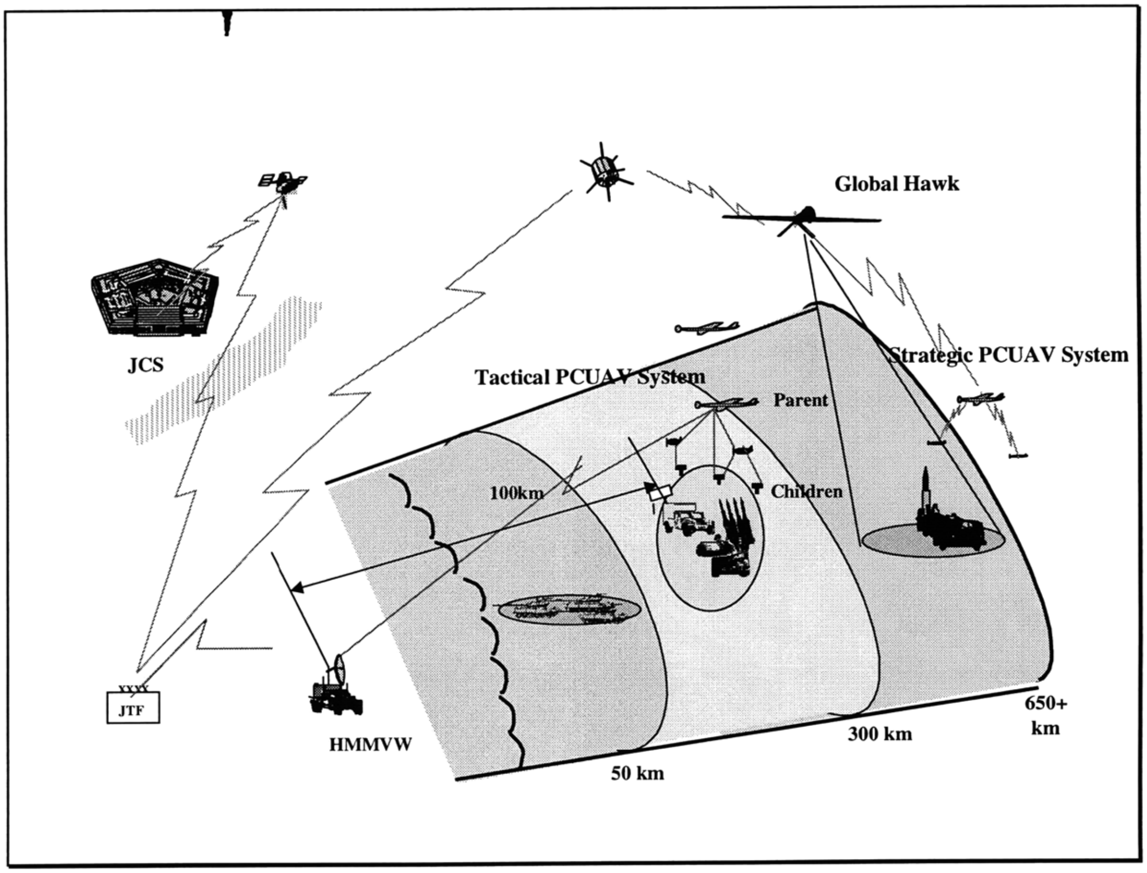

Fig 3.7 PCUAV operations - tactical and strategic roles

3.6 Functional Flow Analysis

The team created an initial version of the functional flow diagram for the PCUAV system. This was modified for each of the three concepts discussed above. After downselecting the forth concept, the different system elements in the architecture and their individual roles were identified. To ensure that some vital functions were not ignored, a detailed functional analysis was performed. A top-level functional flow diagram is shown in Fig 3.8. The details are included in Appendix A. Some elements of the functional flow diagram are briefly described below.

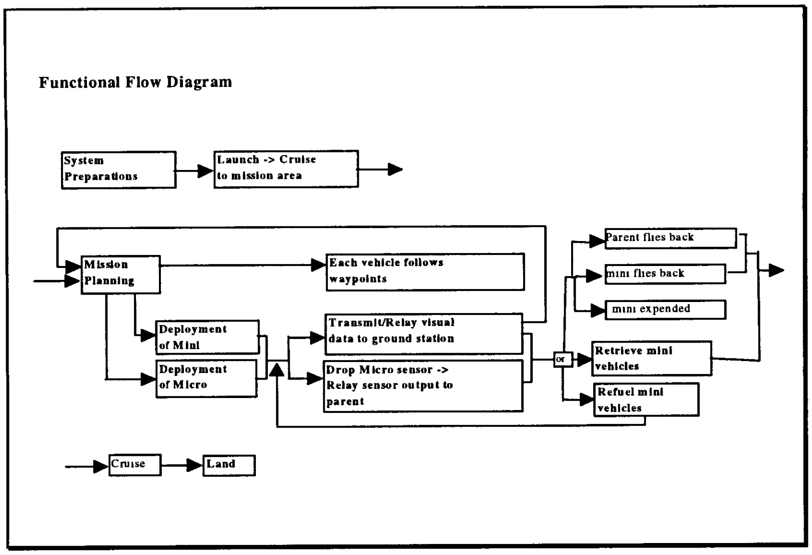

Fig 3.8 Functional flow diagram of the PCUAV system

System Preparation: Parent, mini and the micro systems are assembled together, fueled and their batteries charged. A mission plan for the parent is generated and the waypoints are loaded. Parent is set on the take-off mechanism (e.g., rocket/rail launch) and readied for launch. All sub-system checks are performed.

Launch – Cruise to mission area: The parent, with its mini and micro systems, is launched using a short take-off mechanism and cruises to the mission area by following the designated waypoints. On reaching the mission area, the parent transmits a visual image of the target location to the ground station. The user would then confirm/locate the target.

Mission Planning for the child systems: On confirming the location of the target, mission plans would be generated for each of the child systems. Mission plans consist of a list of waypoints that are time stamped. Activities of various systems involved can be synchronized with the aid of these plans. In the current version it is envisioned that any updates to the child system's mission plan will be transmitted to the parent which would download them to the children. All the mission plans are generated on the ground station with human input.

Deployment of the mini and the micro system: Mini/micro system's electronics are activated and all sub-system checks performed. Wireless communication links between the parent and the children are established. Flight conditions for deployment are verified. The deployment mechanism is activated and one or more children are released.

Receive Visual/Sensor Data from the child systems: While following their flight paths, the child systems gather sensor data and transmit it to the parent (directly in the case of a mini and through the mini in the case of micro systems). Sensor data is envisioned to be mostly video information, which needs a large bandwidth for transmission to the ground station. Hence these images are fused and compressed onboard the parent before transmission to the ground station.

Refueling/ Retrieving: In one of the scenarios envisioned, the mini UAVs are refueled by the parent to sustain the mission. At the end of the mission, the mini UAVs could also be retrieved by the parent and returned to base, or possibly be refueled by the parent and fly back independently.

Fly back/Expended: In the case where the mini UAVs are not recovered, they follow the parent back to the base or would be expendable, as are the micros.

CHAPTER 4

Technology Exploration and Risk Mitigation

Concept IV, described in the previous chapter, was presented at a Concept Design Review (CDR) held at Draper Laboratory to obtain opinions and feedback on the choices made during the trade study and downselection process. Details were reviewed during the CDR and it received a positive response along with some statements of concern. Innovative thought was cited as significant and system complexity was voiced as a concern. In order to assess the degree of complexity involved in the system concept, the team decided to work on identifying the key technologies that must be developed. From the functional flow analysis, technologies required for each of the sub-systems were identified. While an attempt was made to incorporate many clever, creative and unconventional approaches into the design and development of each of the subsystems and their interfaces, existing approaches proved to be more effective in many instances. For example, the team felt that a conventional rocket/rail launch system for take-off and parachute landing system were effective approaches for the launch and recovery of the parent.

The overall aim of the project has been to develop a unique technology or approach. This would require supporting technologies and approaches involving clever, creative and unconventional approaches that have been defined as unobtainia. Because of their nature, unobtainia involve high-risk elements that can jeopardize the project objectives if they are not addressed early into the project. For example, they might require time and effort beyond the resources available to the student team and the project deadlines. They might even be unfeasible with available technologies. These unobtainia were identified and the technologies associated with them explored. Attempts were also made to maximize the use of available components in the sub-system designs.

Novel-Subsystem Technologies/ Approaches Technical Requirements		Vehicle Configurations and Deployment of MINI	Integrated Fuel System	Deployment of Micros and Remote Start.	Parent MINI-Micro TD&C Comm Links	Mission Plan for multiple vehicles	Ground Station for Multiple Vehicles
		1	4	5	3	2	6
Integrated vehicle design	10	5	5	0	0	0	0
Efficient Aerodynamic/Control Design	9	5	0	0	0	0	0
Multiple sensor data fusion	9	0	0	0	1	0	3
Autonomous Guidance, Navigation and Control	8	3	0	0	3	5	0
Stable Platform	7	5	0	0	0	0	0
Expert Mission Planning	7	0	1	0	1	5	0
Rugged / Robust	7	5	3	0	0	0	0
Night Sensor Technology	7	0	0	1	0	0	0
Efficient Data Collection and Processing	6	0	0	0	5	1	3
High Lift Capability	7	5	0	0	0	0	0
Low specific fuel consumption	6	1	0	0	0	0	0
Light Weight Structure	6	5	0	1	0	0	0
Child Vehicle Management and Control	6	0	1	0	5	5	0
Adaptable to multiple missions	5	0	1	5	1	5	1
Modular Design	5	5	3	5	0	0	0
Ground Sensor Precision Landing	4	0	0	5	0	0	3
Open System Architecture	3	1	0	5	1	0	1
Compact Design (to fit in suitcase)	4	1	1	3	0	0	0
		292	108	110	108	136	65

Table 4.1: Unobtainia identification and relative importance

The three-layered architecture of Concept IV involves micro-systems in the lowest layer. Technologies involved with these systems are being developed by CSDL, Lincoln Laboratory and by many DARPA sponsored projects. From discussions with experts working on these projects, it was concluded that an operational MUAV might be available in about 2-3 years. It was decided that the development of MUAVs or technologies associated with them was not a significant aspect of this project, however interfaces to the micro-systems will be developed to make use of them when they will be available. The unobtainia associated with the parent and the mini UAVs have been classified into two categories – *vehicle unobtainia* and *systems unobtainia*. Table 4.1

shows some of these and their relative importance to the technical requirements derived from customers needs.

4.1 Vehicle Unobtainia

The chosen integrated concept has many unique features. Mini aircraft are attached to the parent's wing to provide aerodynamic advantage and added propulsive power. As identified in the functional flow analysis (Fig 3.8), the PCUAV can demonstrate many novel functionalities. These include deployment, mid-air refueling and potential retrieval of mini UAVs by the parent. The unobtainia and risks involved in achieving these features and designs are described below.

4.1.1 Vehicle Configuration and Deployment of Mini UAVs

A number of challenges are involved in the design of parent and mini vehicle configurations and their integration. Various configurations were explored by placing the mini at different locations of the parent. Two planforms – conventional and delta – were used for the parent and the mini. The goal was to find an optimum configuration that would achieve the following objectives.

a) Efficient Vehicle Aerodynamics: Presence of a mini aircraft close to the parent significantly affects the aerodynamics of parent-mini combination. A configuration that offers maximum lift-to-drag ratio is desired. This would tend to give the parent-mini combination increased range and endurance.
b) Stability and Control: Parent-mini configuration should provide a clean and stable separation during the deployment phase. Clean separation would require that the parent design provide enough clearance so that the mini does not hit any of its surfaces during deployment. Stable separation requires parent and mini to remain stable during and immediately after deployment. These considerations hold for refueling and recovery as well.

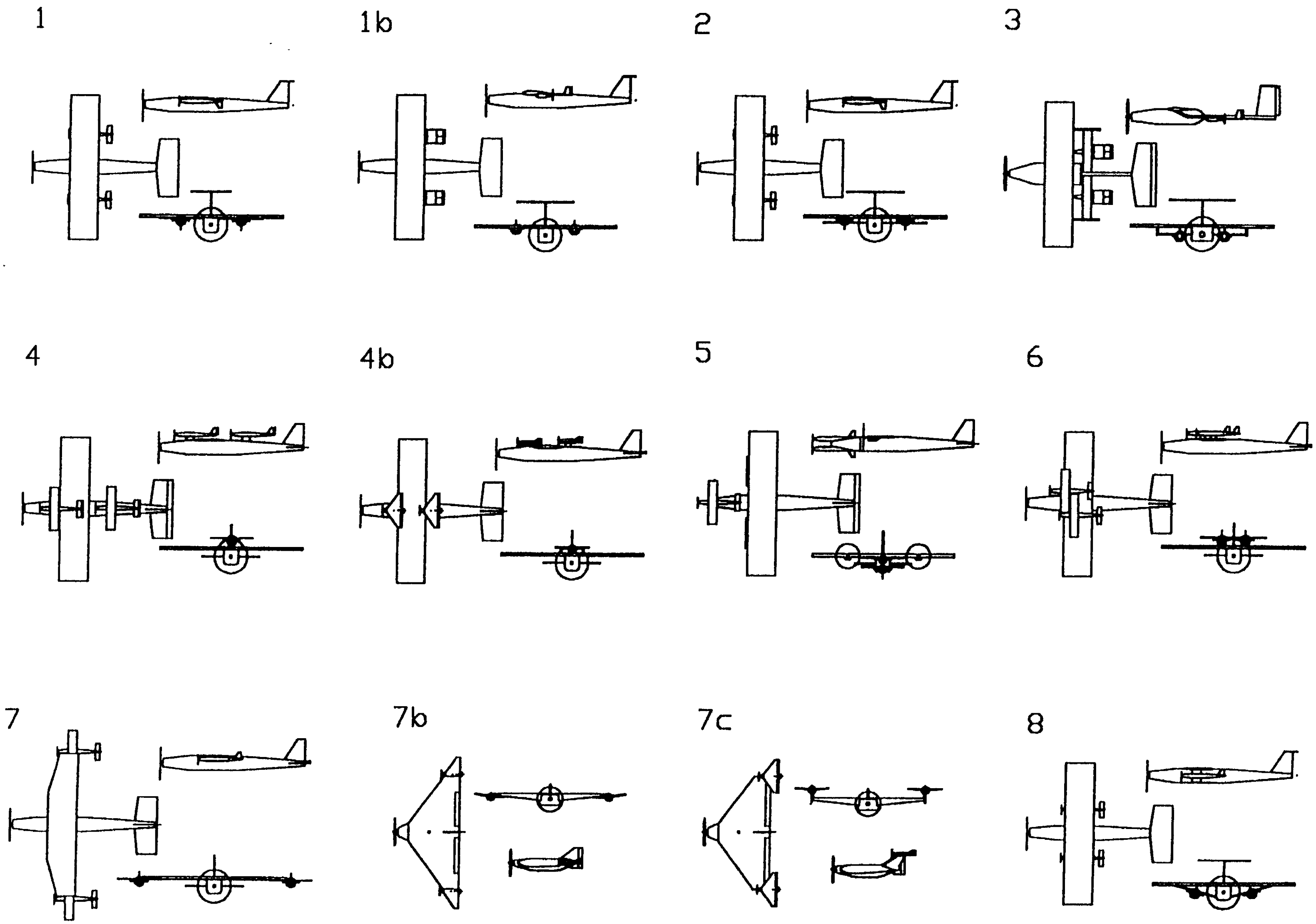

Fig 4.1 Parent – mini integrated-configurations

c) Structural Loads: The mini aircraft should be attached to the parent at locations such that minimal additional strengthening of the parent structure would be required.

Twelve candidate parent-mini configurations and integration layouts, as shown in Fig 4.1, were generated. Analytical aerodynamic performance analysis of some of these integrated parent-mini configurations was performed [7].

Integration-concept 1, 1b, 2 and 3:

In these concepts, mini aircraft are mounted on pylons of the parent. The mini aircraft are located away from the centerline of the parent. Hence they need to be deployed simultaneously. This is necessary so that the parent does not encounter unsymmetrical forces. This requires that the parent should have large control surfaces and results in inefficient operations. The mini aircraft are deployed behind the parent. Soon after deployment, mini aircraft might invert and lose control in the vortices generated in the downwash of the parent. Mini aircraft need to be provided with enough control power to overcome this problem.

Integration-concept 4, 4b, 5 and 6:

To overcome the problems of deploying the mini aircraft in the vortices behind the parent, these concepts were explored. Mini aircraft are positioned above the parent so that they get maximum clearance during separation. After deployment they fly forward. These concepts are expected to have a stable separation, since the vortices behind the mini are less disturbing to the parent than the reverse concepts. Also since the mini aircraft are located along the line of symmetry of the parent, they can be deployed one at a time.

Integration-concept 7, 7b and 7c:

Mini aircraft are placed at wing tips to provide aerodynamic advantage. Effective span of the parent-mini combination is increased by this configuration. However the mini is now in the strong wing-tip vortex .

Integration-concept 8:

Mini wing structure acts as a strut. This can reduce the structural weight of the parent, however this configuration has less aerodynamic advantage than the other concepts.

4.1.2 Integrated Fuel, Data, Power and Mechanical Interface

Integration of the parent and mini is required so that some of the parent's resources, such as fuel and electric power, can be used by the mini and some of the payload capabilities of the mini can be used by the parent. Exchange of these resources, as well as digital information, in-flight can be accomplished by an interface[8]. Features needed for such an interface are detailed below.

a) Preliminary studies show that for a two-hour mission, a mini aircraft would require 3.2 kg of batteries if it were propelled by a 0.5 horsepower electric motor. For the same mission and power setting, it would require about 180g of fuel if it were propelled by a combustion engine. Hence, it was decided that a combustion engine rather than batteries should power a mini. Unreliability associated with remote starting of combustion engines significantly risks the execution of a mission. Hence it is envisioned that engines of the mini be kept running from the start of the mission. Since the fuel tanks of mini aircraft are significantly smaller than for the parent, a fuel transfer interface between the parent and mini was envisioned. In addition, while a mission is being executed, the mini aircraft could be refueled by the parent through the same interface.

b) Power interface: The mini aircraft have limited weight carrying capacity. Hence, the size of their batteries is restricted. This would require the parent to recharge the mini aircraft's batteries during cruise. This requires an interface between the parent and the child through which power could be transmitted.

c) Data Interface: The mini aircraft carry payloads (e.g. cameras, radars) which can be used by the parent while they are integrated with the parent. These payloads are connected to parent through a data interface.

d) Mechanical Interface: Deploying the mini aircraft would require a mechanical release system that can provide a clean separation. The same interface is envisioned for refueling and retrieval of the mini aircraft.

4.1.3 Deployment of the Micro Systems

Micro systems are deployed in pallets that are conceptually similar to conventional airdrop cargo systems. DARPA has been supporting projects to build micro systems of the size 6" or smaller to be used by individual soldiers. These systems, which include MUAV, micro helicopters, ground robots etc., will be packaged inside a PCUAV pallet with internal dimensions of 6"X6"X6". The deployment mechanism has been referred to as the cargo delivery system, which has the following features:

1. Accommodates MAVs
2. Accommodates double-sized pallets for larger payloads
3. Uses parent's system for actuation
4. Pallet can eject cargo MAV on ground or at specified altitude
5. Pallet consistently lands upright without damaging cargo
6. Pallet might contain fuel for extended parent flight-time

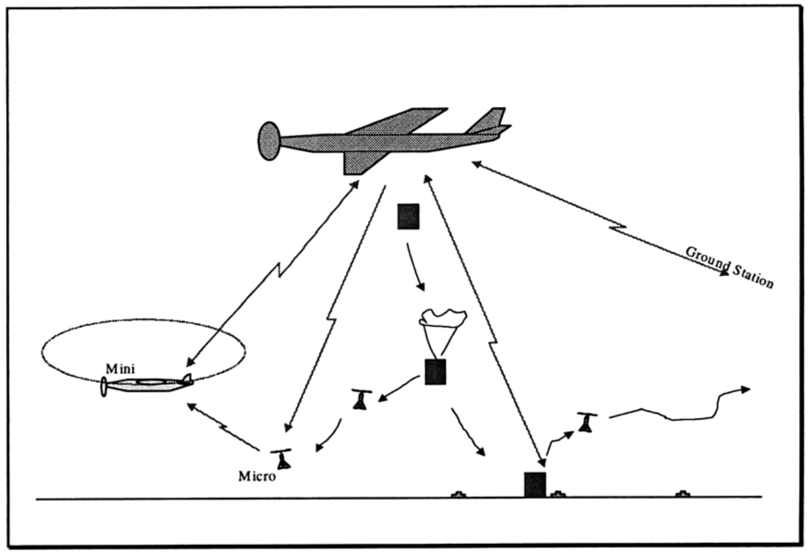

Fig 4.2 Deployment of the mini systems using pallets

Fig 4.2 shows the deployment of a micro UAV from a pallet. The micro UAV can be deployed in mid-air from the side of the pallet. If the micro-UAVs are helicopters, they can be launched from the top of the pallet after the pallet lands. Ground robots can drive out of the side of the pallet.

The cargo delivery system consists of two distinct subsystems: the pallet which holds and delivers the cargo to its target and the housing mechanism that remains fixed to the parent. A pallet mock-up was built to study the feasibility of the design [12].

The pallet system consists of the pallet-structure, release mechanism and a parachute. The structure of the pallet is made of two "C" shaped sections that connect together to form a cube. The lid houses the parachute and the base unit houses the release mechanism. In addition, the pallet has fins on its edges that stabilize it during the deployment phase. Fig 4.3 shows a sketch of the pallet and its components.

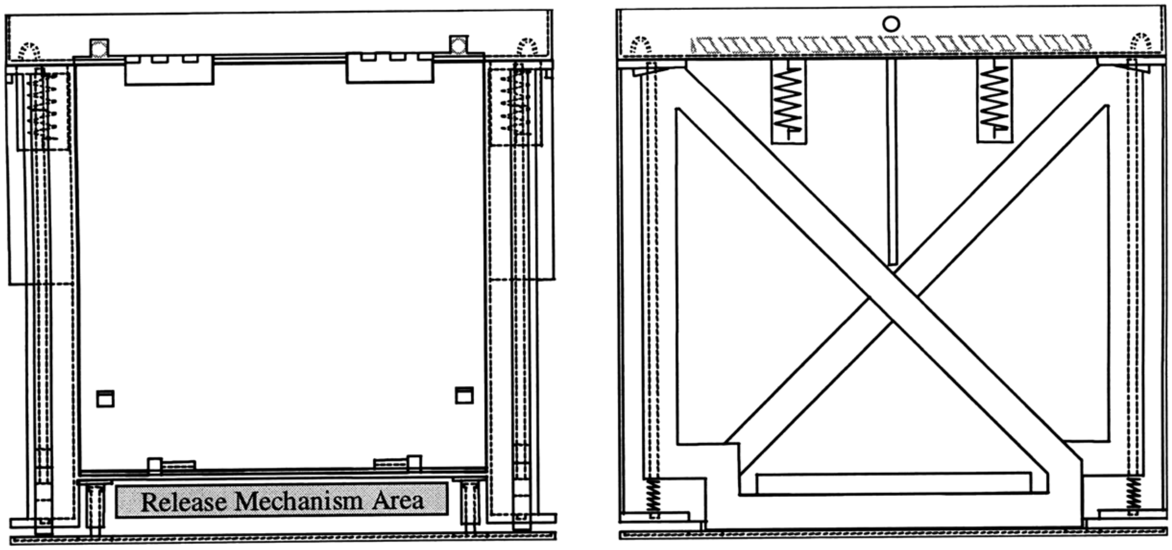

Fig 4.3 Pallet system- consists of the lid (left) and the base (right)"C" sections (Courtesy of Michael Parkins)

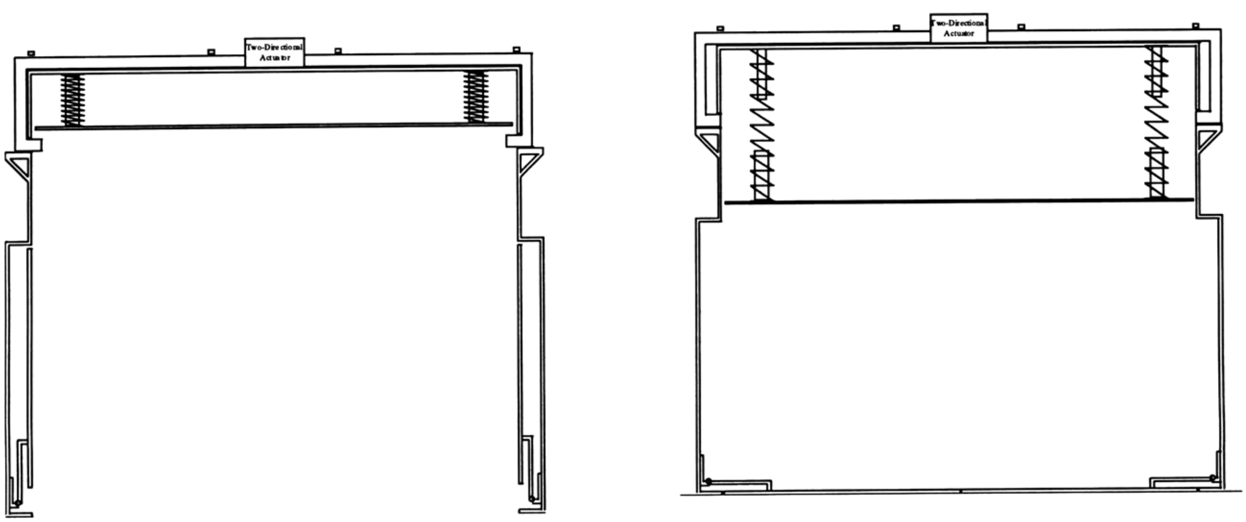

Fig 4.4 Pallet housing and deployment mechanism-"Hold" (Left) and "Post-Release" (Right) setup (Courtesy of Michael Parkins)

The housing mechanism manages the bay doors as well as the locking device for the pallet. A pallet is pushed up into the bay of the parent to load it onboard. Doors get pushed into their vertical positions, and the "rolling pusher plate" is pushed upward against the top springs. The springs push the plate and the pallet down with the help of gravity. As the pallet exits the parent, the doors are pushed into their horizontal position by the springs.

4.2 Systems Unobtainia

In addition to the vehicle challenges, which have been identified in the previous section, the project involves systems-level challenges due to the system-of-systems nature of PCUAV. Most important among them are the communication links between the parent, mini, micros and the ground station.

4.2.1 Parent, Mini and Micro Communication Links

The parent, mini and the micros carry cameras as their payloads. These can be replaced with other suitable sensors for different missions. Cameras were chosen, as they required the maximum bandwidth for transmission of information. Signal transmission between any two nodes can be accomplished by either analogue RF or digital modes. Wireless Local Area Network (WLAN) was considered for the communication between the parent and the mini aircraft.

Personal Computer Memory Card International Association (PCMCIA) has developed credit card sized WLAN devices. These commercial-off–the-shelf (COTS) computer cards are portable and have been considered for the PCUAV parent-mini communications. These systems have a maximum range of about 1km and a maximum bandwidth of 2Mbps. Some of the advanced WLAN systems offer the capability of communications between any two nodes. Hence, the parent can communicate with either of the mini aircraft with the same communication system. In addition, payload data and telemetry can be multiplexed onboard the mini before transmission to the parent. The micro-systems communicate with the mini aircraft through analogue RF links. The images obtained from the mini and the micros are compressed onboard the parent and retransmitted to the ground station. A high power RF transceiver is used for communications with the ground station.

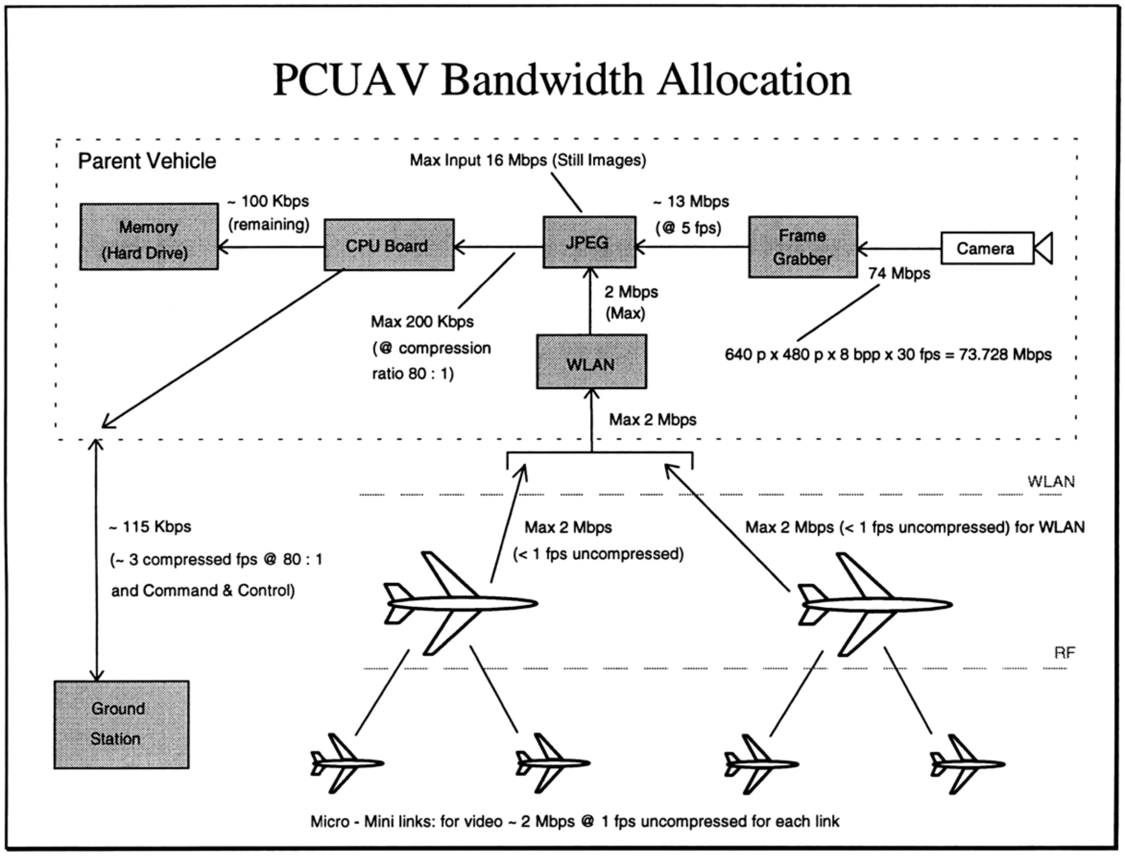

Fig 4.5 Communication links between the parent, mini and micro systems (Courtesy of Alexander Omelchenko) .

4.2.2 Ground Station

A number of UAVs are currently operated by the U.S. Army and the U.S. Marine Corps. Many more are under development as mentioned in Chapter 2 (Fig 2.1). A common ground station, also known as the Tactical Control System (TCS) [14], has been proposed that would be compatible with most of these UAVs. TCS is the software, software-related hardware and the extra ground support hardware (antennae, cabling, etc.) necessary for the control of the Tactical Unmanned Aerial Vehicle (TUAV), and Medium Altitude Endurance (MAE) UAV, and future tactical UAVs.

The ground station for the operational PCUAV has been envisioned to have features similar to the TCS. This would enable easy deployment of the PCUAV ground station to an operational system, requiring minimum changes and minimum training of operators.

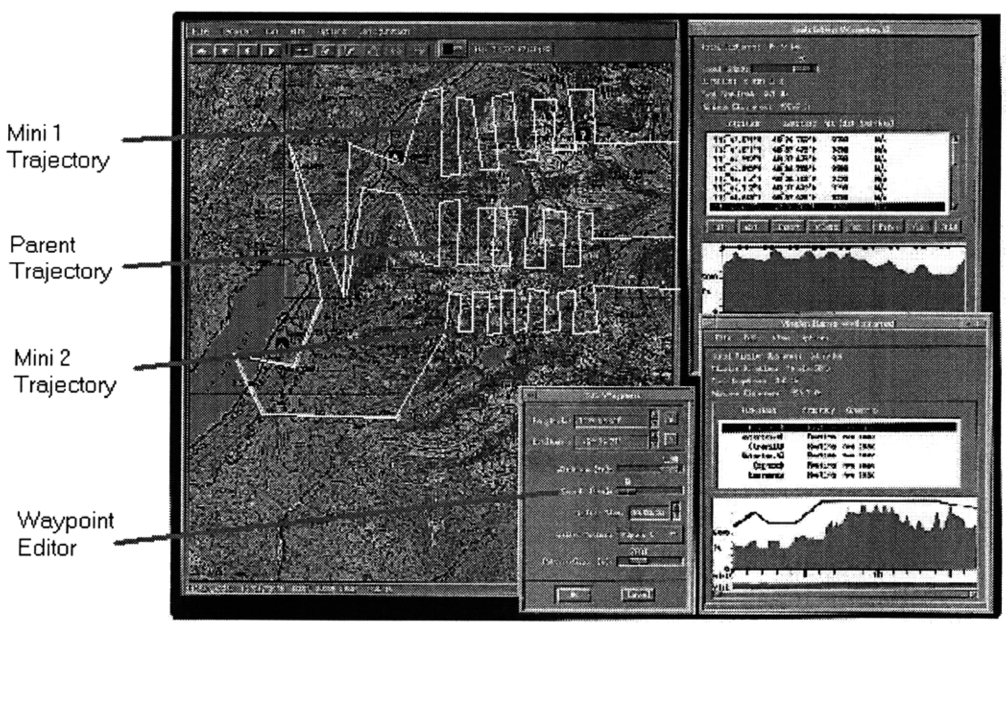

Fig 4.6 Ground station user interface for PCUAV

The initial PCUAV ground station design is based on some of the features available with CDL Systems ground station [3]. This system was used for the Outrider program. The ground station will consist of two terminals - the Real Time (RT) terminal for controlling features that require immediate attention and the Non-Real Time (NRT) terminal for features requiring lesser attention.

The challenge in designing the ground station for the PCUAV system lies in the user interface. Significantly more information is obtained from the PCUAV system than is the case for conventional UAVs because the parent, minis and the micros all carry sensors. A COTS ground station can be converted into a ground station for PCUAV system with some modifications. A typical ground station user-interface for multiple vehicles is show in fig 4.6

4.2.3 Mission Planning for Multiple Vehicles

The degree of complexity associated with mission planning is defined by the degree of autonomy of the PCUAV system. Autonomy of an unmanned system depends on its ability to sense its own state and the environment. To reduce the risk to the project, low levels of autonomy are incorporated in the two-year student project.

Autonomous waypoint navigation: The mission profiles of all of the systems will consist of a set of way points and the desired state of the system at those points (loiter, hover, continue flight etc.). The vehicles will fly autonomously between any two waypoints and control and modify their state accordingly.

Autonomous return to base (in case of an aborted mission): If the communication link between the parent and the ground station breaks down, the PCUAV (parent and mini aircraft) will return to the ground station.

Mission plans are specific to a given mission. Since a large number of mission have been identified, a general procedure for determining the mission plans for the various systems involved is presented below:

1. Waypoints to the target area are loaded into the parent before launch.
2. When the parent approaches the target area, images of the area are sent back to the ground station.
3. The human operator identifies potential targets in the image and designates their geo-locations as goal-points for the mini and micro systems.
4. With the help of the software at the ground station, the human operator generates mission plans for each of the vehicles.
5. Mission plans for all systems are uplinked to the parent. The parent then loads the respective mission plans into the child systems.
6. On receiving the execute command or at a preset time, each vehicle follows its waypoint designated plan.

Dynamic Retasking: While the predetermined mission plans are being executed the operator may decide to modify some of the waypoints. The modified waypoints are validated by the ground station to check that all constrains are satisfied and then uplinked to the parent. The parent then loads the new waypoints into the respective child systems.

Challenges in mission planning involve keeping the mini and micro systems within communication range. Since all the systems are moving relative to each other in three dimensions, algorithms need to be developed to generate waypoints such that all the aircraft operate within this constraint. In addition, mini and micro systems have limited resources - batteries and fuel. Mission plans should optimize the utilization of these resources.

The team is in the process of identifying and acquiring software that has been used for mission planning on other unmanned systems. This will be modified for the specific application of the PCUAV system.

CHAPTER 5

Project Management

The PCUAV project started in June 1998. The project participants included graduate students, undergraduate students, and faculty members from the Department of Aeronautics and Astronautics. In addition, engineers from CSDL were involved in providing necessary information and feedback. A list of the members actively involved in the project is included in Appendix B. At the beginning of the project, the author was asked to lead the PCUAV student team. The author played the role of a student project manager and the main responsibilities included planning and coordinating the work of the project participants. This was a unique opportunity to learn hands-on management of an aerospace project. The author was given ample freedom by the faculty in making decisions and running the project.

5.1 Project Plan

At the beginning of the project, a two-year master plan was drafted. After getting the consensus of the project participants, the plan shown in Fig 5.1 was established to guide the engineering work, define the team deliverables and conduct the project reviews. It shows the various stages of the project, from conception, design and implementation to operation. The first year team's efforts, involving execution of the first half of the above mentioned plan, can be described in three phases –

- Requirements Analysis,
- System Concept Development
- Preliminary Design, Risk Assessment and Mitigation

Project timelines and activities during these phases are included in Appendix C.

5.2 Team Structuring and Work Breakdown

The student team was divided into small groups of two or three in each of these phases. At the end of the phase, the groups were dissolved and the entire team worked together to draw conclusions and prepare presentations. All the students met once every week to discuss their progress. These group activities along with the weekly meetings ensured that all were aware of the various aspects and challenges involved in the project.

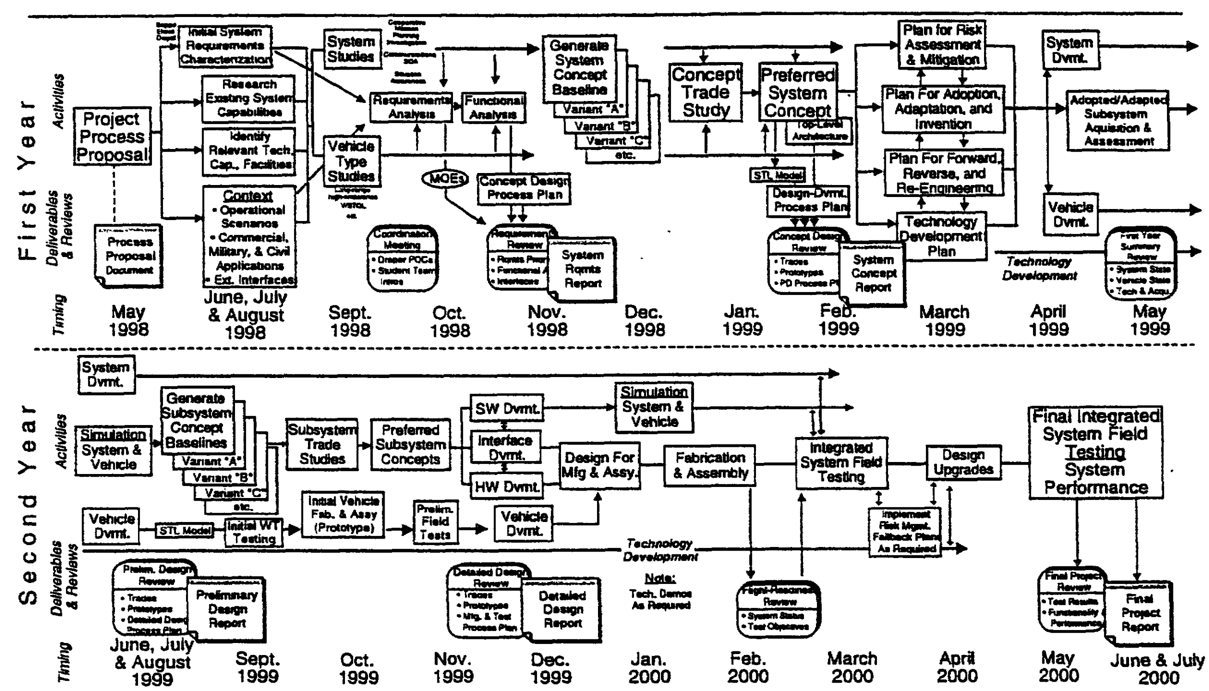

Fig 5.1 Project master plan

5.2.1 Phase I – Requirements Analysis - Fall 1998

The requirements analysis phase focused on requirements development and functional analysis. Three groups were formed to work on each of the following

a) Requirements Analysis –This group identified and established initial contacts with potential customers. Potential applications and mission scenarios were generated from discussions with the contacts.
b) Systems Studies – This group investigated the functions involved in the system-of-systems aspect of the project. Technological challenges and potential solutions to execute some of the unique functions were identified.
c) Vehicle Studies – This group researched the capabilities of existing systems. Characteristics of various UAVs were catalogued.

After each of the groups completed their research, the entire team worked on customer needs prioritization and identified technical drivers for the project as been described in Chapter 2. This phase concluded with a requirements review at CSDL.

5.2.2 Phase II – Concept Development - Winter 1998-99

Concepts were generated in an attempt to satisfy the customer needs and potential mission requirements. Three concepts were selected for further investigation. Groups were formed to develop each of these concepts to satisfy a single mission. Towards the end of this phase, the entire team worked together to generate a preferred system concept. The concepts and the process were described in Chapter 3. This phase concluded with a concept design review at CSDL. During this phase the students were also investigating technologies and components required for various sub-systems.

5.2.3 Phase III – Preliminary Design, Risk Assessment and Mitigation - Spring 1999

Two groups were formed to develop the vehicle and avionics designs. These groups consisted of students and faculty with expertise in various fields. Technologies and approaches associated with mitigating the risks involved in achieving the vehicle unobtainia and systems unobtainia were investigated by the respective groups.

While the students were involved in the design of the system, it was felt necessary to keep track of developments in the field of UAVs and continue to work on potential missions, competitors and identify new missions. An executive group comprising the faculty members and engineers from CSDL was formed to address these issues.

5. 3 Project Coordination

In the role of a student project manager, the author planned and coordinated meetings, made announcements, arranged for guest speakers and assigned responsibilities after consultation with the faculty and the students. The first year of effort involved investigating the various aspects of the project and generating innovative ideas. An immense amount of information was gathered during the course of the project. An efficient flow of information was vital for effective decision making and overall success of the project. The following were the activities of the team during the first year.

5.3.1 Thursday Morning Meetings

These are regular weekly meetings attended by all project participants. They usually involved a presentation by the students about the work performed during the week. Feedback from the faculty and participating engineers from CSDL was sought.

5.3.2 Guest Speakers

Occasionally, experts from CSDL and outside organizations were invited to make presentations relevant to the PCUAV project. These covered a wide range of topics including "Requirements for TUAV," "DRAPER/Lutronix MAV" and "Tactical Ground Station." Other department-organized talks relevant to the project were attended by some of the students.

5.3.3 Interaction with CSDL engineers

While exploring the technologies needed for developing the concepts, students consulted with experts at CSDL. Individual students contacted them through e-mail or phone and then meetings were set up. These meetings and their agenda were announced on the student mailing list so that others interested in a discussion could attend.

5.3.4 Sub-Group Meetings

As mentioned in the previous section, groups were formed to investigate design variants or different subsystems. They were comprised of two or three students working closely with faculty members. These groups met regularly and the results of their efforts and discussions were presented in the Thursday morning meetings.

5.3.5 Student Team Meetings

These meetings were less formal and mainly focused on coordinating the efforts among the students. Data was exchanged and the roles of each team member were clarified. Project plans were also discussed during these meetings.

5.3.6 Review Presentations

The outlines for the presentations were decided in advance. Responsibilities were then assigned to each student to work on specific sections. Feedback was obtained during the requirements review and the concept design review.

5.3.7 Documentation

Project files were maintained which contained the materials discussed in the Thursday meetings, trip reports, requirements and concept design review presentations, project plans and schedules.

5.3.8 Information Gathering

The Internet was used effectively in this project for two main purposes – gathering information and communicating between team members.

Most of the information that was needed for compiling the COTS database [13] was obtained from the Internet. This consisted of data and specifications of subsystems relevant to the project. Leads from CSDL engineers or a web search led to identifying many components. Sometimes requests were also posted on Newsgroups.

Online product catalogues gave instant information that could be used in the designs. Vendors were contacted through e-mail and more information about their products was requested and obtained.

5.3.9 Communications

As mentioned above many activities were organized during the course of the project. Decisions were made during meetings. E-mail was used to communicate with all the project participants. Two sets of mailing lists were used. The main channel of distribution of information to all people involved with the project was through a mailing list, pcuav@mit.edu. Any general announcements and interesting findings were reported to this list. The students used a smaller list, uav@mit.edu, to exchange information that was necessary for their sub-group designs.

The e-mails of the PCUAV mailing list were being regularly archived into webpages on a secure web-server. Project participants had access to these webpages through a password.

CHAPTER 6

Project Status, Recommendations and Conclusions

6.1 Project Status

During the first year of the PCUAV project the following objectives were achieved:

1. Customers and their needs were identified and prioritized.
2. Mission scenarios and systems concepts were generated.
3. A preferred concept involving a three-tier architecture was selected.
4. Vehicle and systems unobtainia were identified.

At the end of the first year, two groups were formed to work on the vehicle unobtainia and the systems unobtainia. In addition, these groups also worked on the vehicle and electronic systems preliminary designs and their variants.

The current project schedule, Spring 1999, for the two groups is presented in Appendix C. This schedule corresponds to the later parts of the first year project plan shown in Fig 5.1. Some of the milestones shown in the project schedule have not been reached. The following have been identified as possible reasons.

During phase II, the team was attempting to find a system concept that would satisfy all potential customers. This process took more time than planned and resulted in the Concept Design Review (CDR) being postponed by nearly one month. Due to this slip in schedule, Phase III started a month late. Thus, the time available for technology exploration and risk mitigation was reduced from four months to three months.

6.1.1 Vehicle Group Status

From the functional flow analysis, components required for various sub-systems were identified. Some of the components are shown in the preliminary vehicle inboard-layouts in Appendix D. In addition, 3-D CAD models were generated for some of the vehicle configurations.

Aerodynamic simulations for various configurations of the parent and the mini were performed to determine the optimum integration concept. Preliminary design of the fuel transfer and separation mechanism has been done. A prototype pallet has been designed and built [12]. The housing for the pallet has been designed but a prototype has not yet been built.

6.1.2 Electronic Systems Group Status

The parent and mini avionics architectures are currently under development. Most of the hardware components have been identified. Some of these are shown in the parent avionics architecture in Appendix D. Variants of this design are being worked on.

COTS components for communications between parent and child systems have been identified. COTS hardware for communication between the parent and ground station 100 km apart could not be found.

While independent mission plans for multiple single unmanned systems can be achieved with existing software, PCUAV mission planning involves the challenge of coordinated operation of multiple systems within constraints. These constraints include communication range and vehicle resources. No effort has been made to develop this software so far.

6.2 Recommendations

During phase I and phase II, with the use of QFDs and a thorough understanding of customer needs, the team was successful in focusing on the key aspects of the project. A three-tiered architecture was generated that could potentially satisfy all the missions by using relevant systems at each level. However, in phase III schedule slips were encountered. The work needed to prove the feasibility of the unobtainia has not been completed. It is recommended that the second year team should concentrate on proving the feasibility of the unobtainia that have been identified

Project schedules should take into account all possible factors, such as availability of wind tunnels, thesis submission dates, etc. If slips occur in the previous phase of the project, effort should be made to contain its spread into the next phases of the project.

Several alternate proposals were made during the first year that deviated from the master plan. However they ended up being biased towards a specific technology or approach and did not take into account all the necessary factors driving the project. For example, it was proposed that the thrust of the project should be in the development of micro systems as it offered many unobtainia. A two-year project plan involving micro-fabrication technologies was proposed. However, the team realized that this proposal did not meet many of the project goals.

For the next year, it is suggested that the second part of the project master plan (Figure 5.1) be considered for implementation. The master plan addresses the project at the highest level and still offers flexibility to accommodate innovative ideas at each phase of the project.

Stability of the aircraft after separation is an issue not yet addressed. Wind tunnel tests are strongly recommended to determine if the integration-configurations maintain stable flight during deployment.

While the Internet is a vital source of information, finding relevant information is difficult. Much time can be wasted searching through webpages that look interesting but are not relevant to the project. It is recommended that experts in the field be consulted to reduce the scope of Internet searches.

6.3 Conclusions

The goal of the project, designing and developing a parent-child system-of-systems concept was set before the students joined the project. This gave the team an opportunity to focus on the project and aim higher. The QFD matrices were effectively utilized to prioritize customer requirements, technical requirements and the unobtainia. The unobtainia can be traced back to the goals of the project through Table 4.1, 2.2 and 2.1.

A three-tier system concept evolved from a systematic approach of requirements analysis and concept development. A wide range of missions can be executed by this concept because of the flexibility provided by its system-of-systems nature.

The PCUAV project offered the students, faculty and everyone involved an exciting and unique opportunity to conceive and design a novel aerospace system. A high degree of complexity is involved in this project due to the involvement of multiple systems and their interactions with each other. The challenges involved in identifying and achieving the objectives offered many learning opportunities. A better understanding of the systems approach applied to aerospace design was achieved.

Many interesting lessons were learnt in the management of a team. While E-mail was effective in transferring files between the students, it cannot be used for any of the design activities. Direct exchange of thoughts and ideas stimulates innovative thinking, which is necessary for this project.

The author firmly believes that the PCUAV is a promising project with potential markets for many of its applications.

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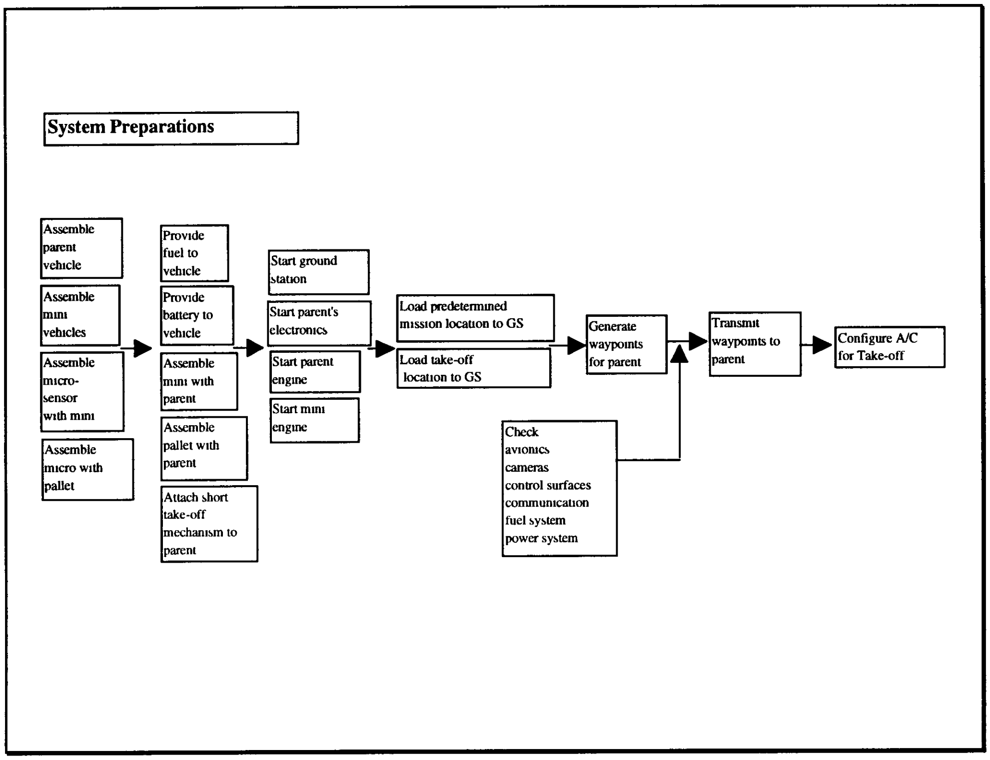
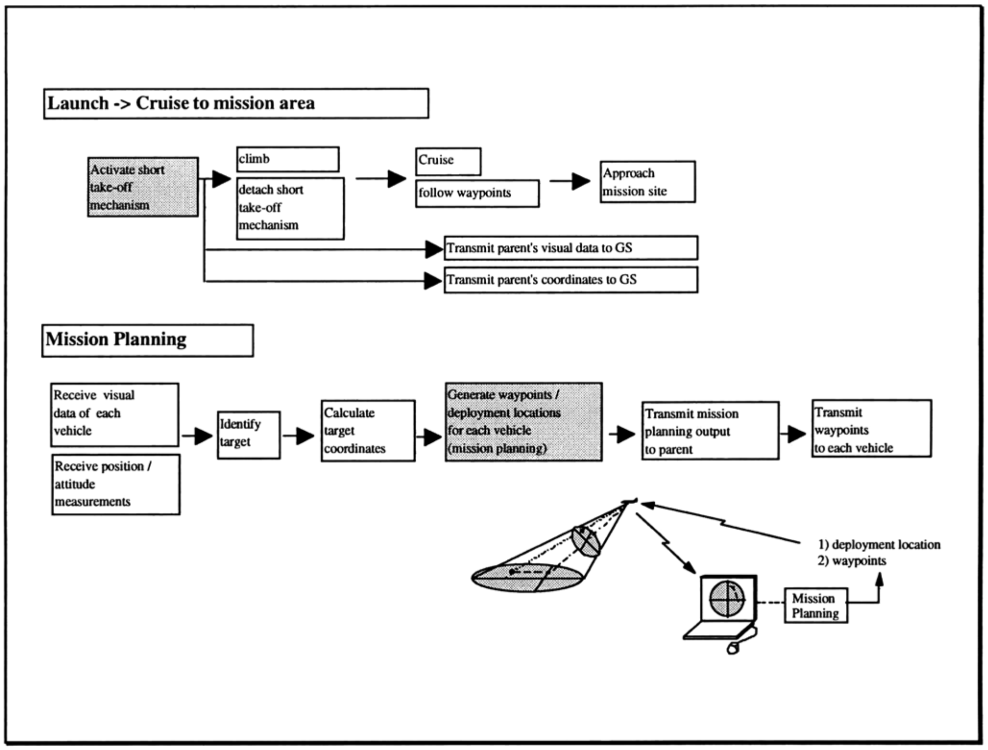
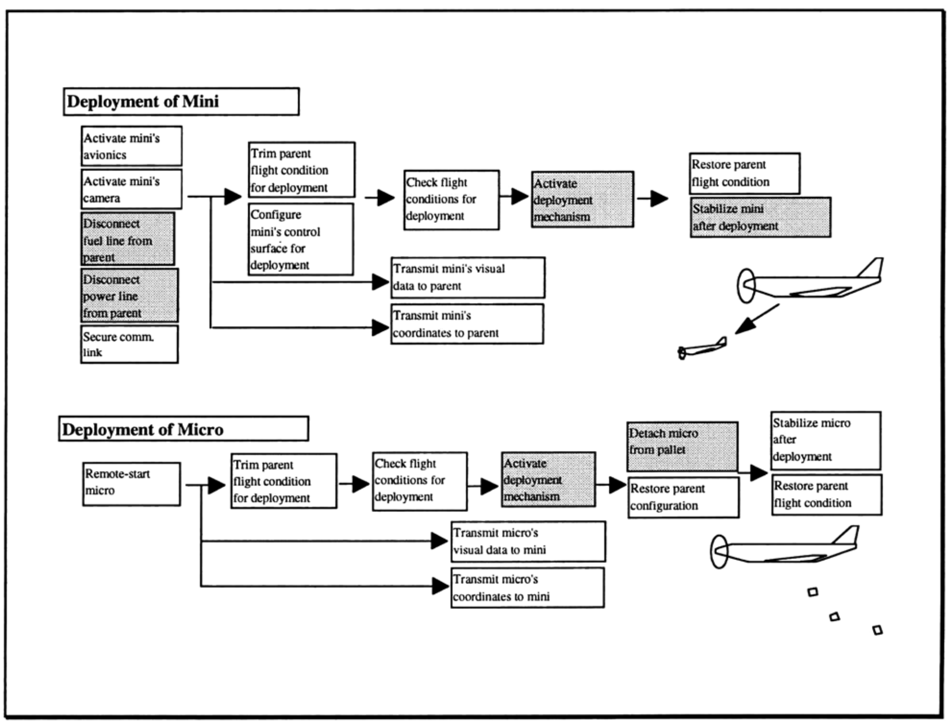
APPENDIX A – Functional Flow Diagrams





Launch -> Cruise to mission area
Activate short take-off mechanism
climb
detach short take-off mechanism
Cruise
follow waypoints
Approach mission site
Transmit parent's visual data to GS
Transmit parent's coordinates to GS
Mission Planning
Receive visual data of each vehicle
Receive position / attitude measurements
Identify target
Calculate target coordinates
Generate waypoints / deployment locations for each vehicle (mission planning)
Transmit mission planning output to parent
Transmit waypoints to each vehicle
1) deployment location
2) waypoints
Mission Planning



Deployment of Mini
Activate mini's avionics
Activate mini's camera
Disconnect fuel line from parent
Disconnect power line from parent
Secure comm. link
Trim parent flight condition for deployment
Configure mini's control surface for deployment
Check flight conditions for deployment
Activate deployment mechanism
Restore parent flight condition
Stabilize mini after deployment
Transmit mini's visual data to parent
Transmit mini's coordinates to parent
Deployment of Micro
Remote-start micro
Trim parent flight condition for deployment
Check flight conditions for deployment
Activate deployment mechanism
Detach micro from pallet
Restore parent configuration
Stabilize micro after deployment
Restore parent flight condition
Transmit micro's visual data to mini
Transmit micro's coordinates to mini

Transmit/Relay visual data to ground station

Parent

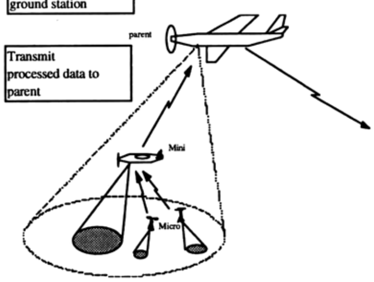
Collect visual data from parent, mini, micro → Process visual data (compression, multiplexing) → Transmit processed data to ground station

Mini

Collect visual data from mini, micro → Process visual data (compression, multiplexing) → Transmit processed data to parent

Micro

Transmit visual data to mini



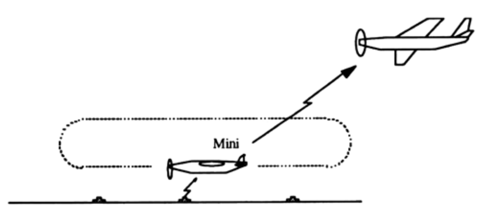
Each vehicle follows waypoints

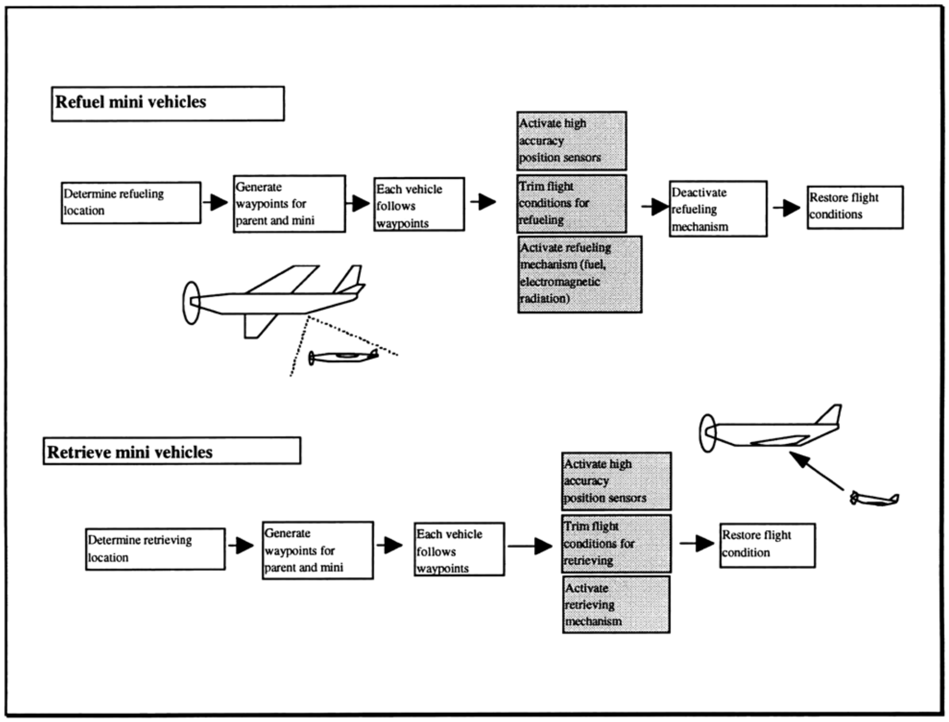
Receive series of waypoints

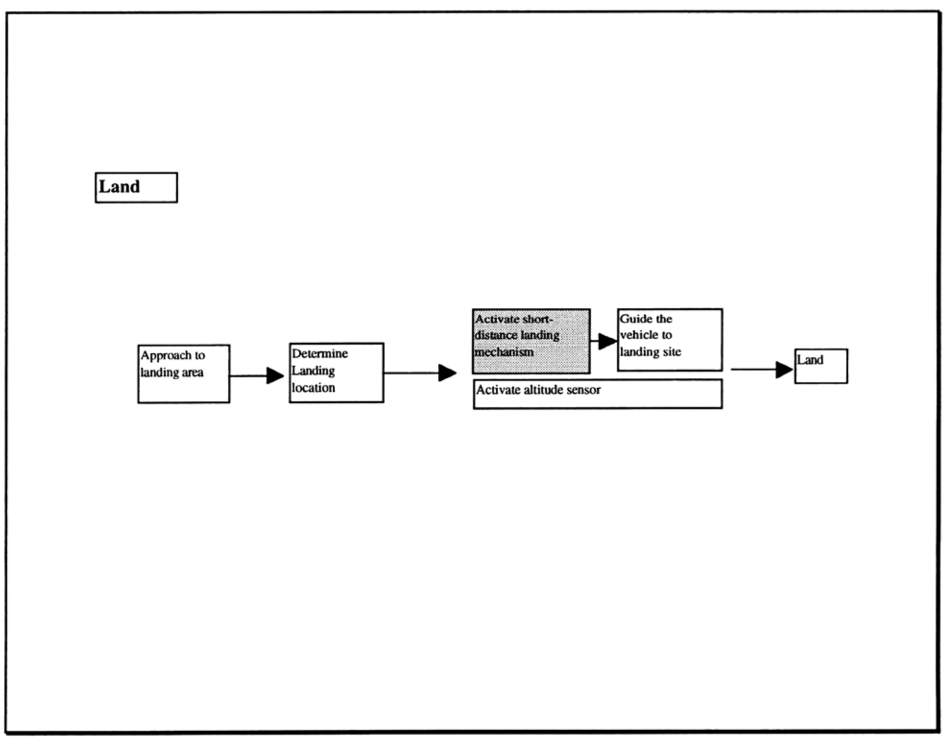
Receive measurements of flight control sensors → Estimate required state variables for flight control → Calculate control input for each actuator → Send control input to each actuator

Drop Micro sensor ->
Relay sensor output to parent

Receive coordinates of drop area of micro-sensors (ground -> parent -> mini) → Trim mini at low altitude flight condition / Activate altitude sensor → Activate drop mechanism / Store the coordinates of the drop points → Close the door → Flies back over the drop locations → Remotely activate micro sensors / Collect micro sensor data → Relay the data to parent




Refuel mini vehicles
Determine refueling location
Generate waypoints for parent and mini
Each vehicle follows waypoints
Activate high accuracy position sensors
Trim flight conditions for refueling
Activate refueling mechanism (fuel, electromagnetic radiation)
Deactivate refueling mechanism
Restore flight conditions
Retrieve mini vehicles
Determine retrieving location
Generate waypoints for parent and mini
Each vehicle follows waypoints
Activate high accuracy position sensors
Trim flight conditions for retrieving
Activate retrieving mechanism
Restore flight condition


Land
Approach to landing area
Determine Landing location
Activate short-distance landing mechanism
Guide the vehicle to landing site
Activate altitude sensor
Land

APPENDIX B – Project Participants

NAME	e-mail
MIT Faculty	
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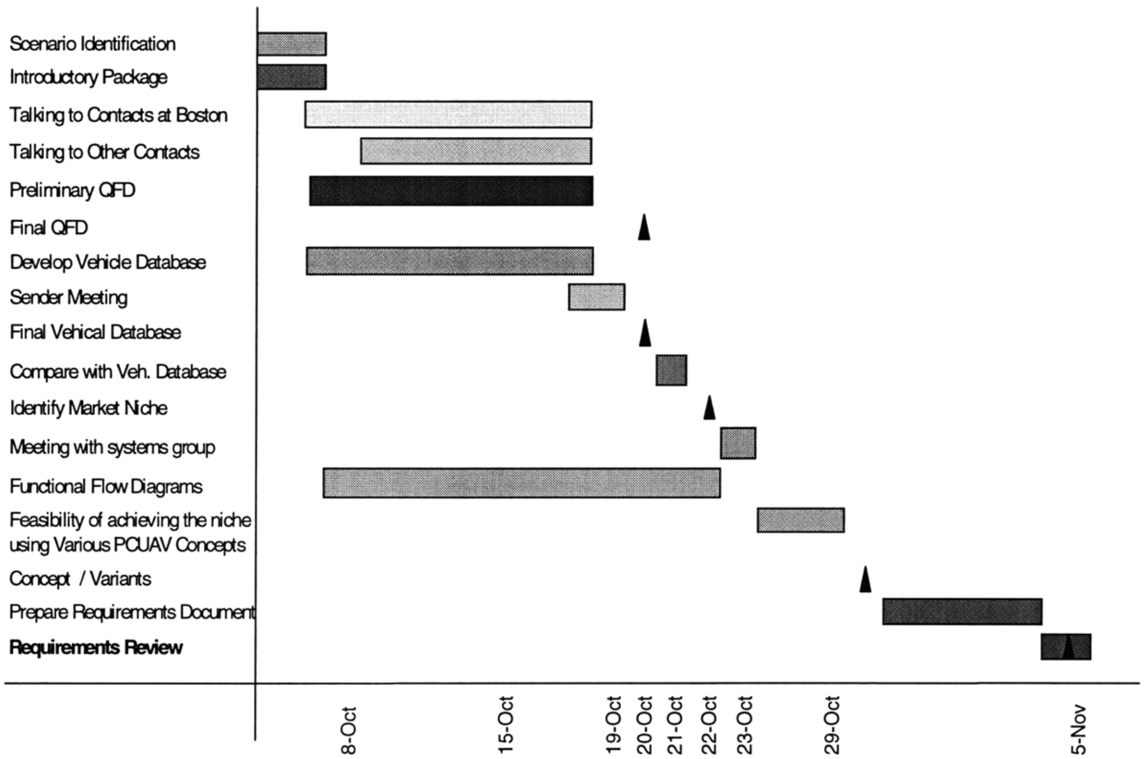
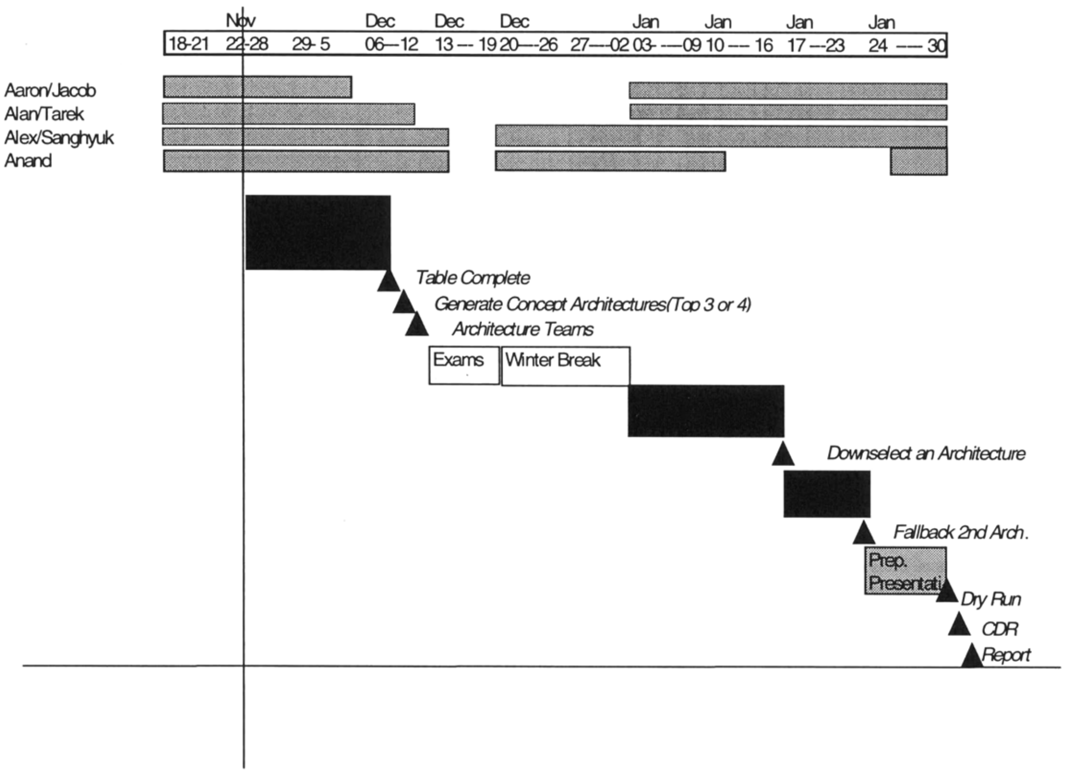
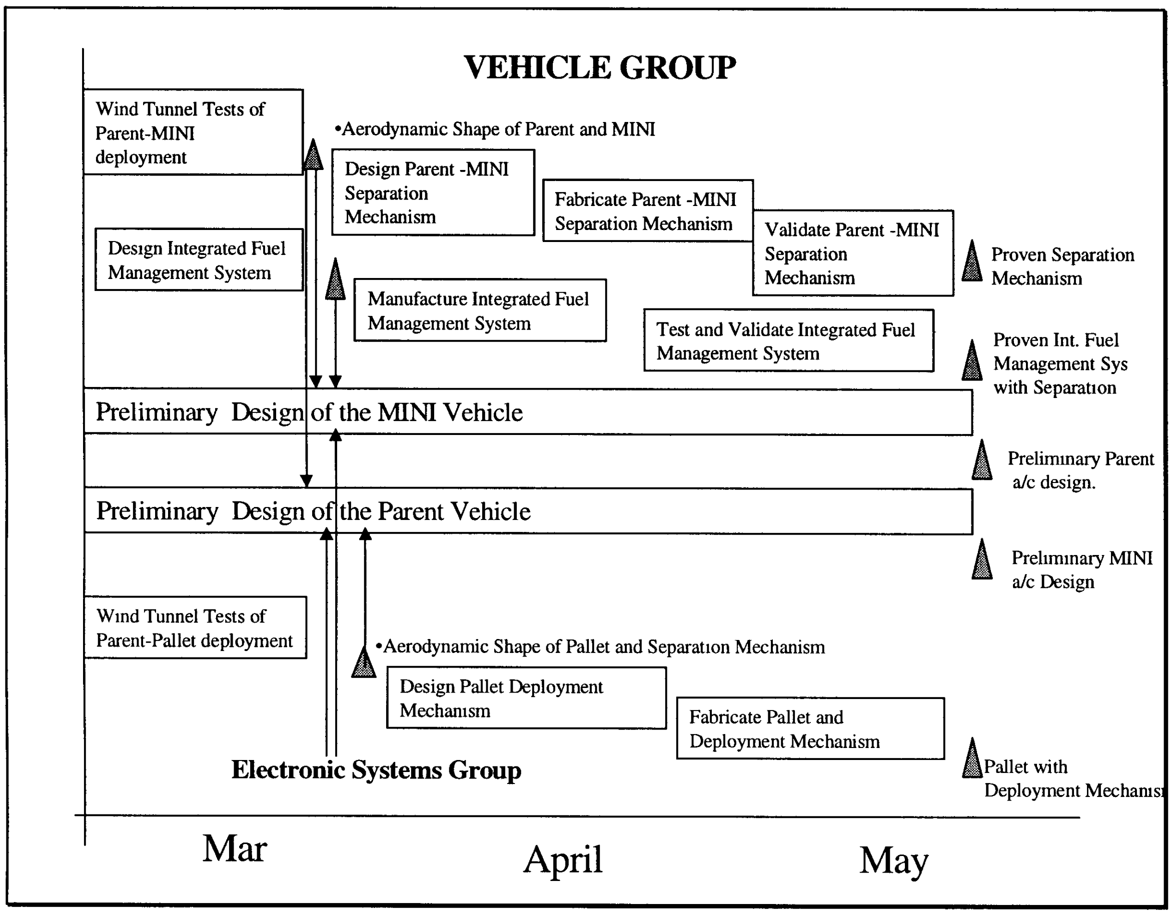
APPENDIX C – Project Schedules



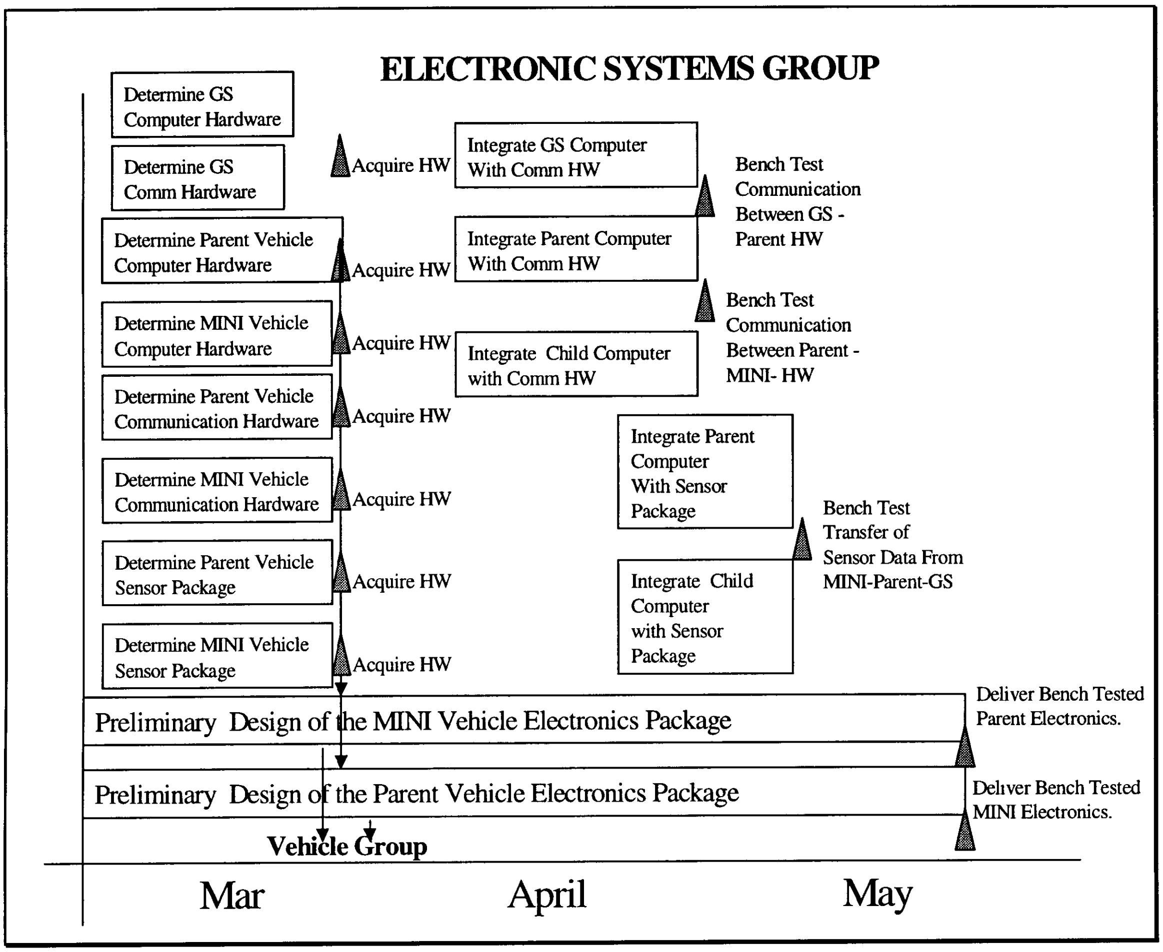
Fall-1998



Winter-1998-99


VEHICLE GROUP
Wind Tunnel Tests of Parent-MINI deployment
•Aerodynamic Shape of Parent and MINI
Design Parent -MINI Separation Mechanism
Fabricate Parent -MINI Separation Mechanism
Validate Parent -MINI Separation Mechanism
Proven Separation Mechanism
Design Integrated Fuel Management System
Manufacture Integrated Fuel Management System
Test and Validate Integrated Fuel Management System
Proven Int. Fuel Management Sys with Separation
Preliminary Design of the MINI Vehicle
Preliminary Parent a/c design.
Preliminary Design of the Parent Vehicle
Preliminary MINI a/c Design
Wind Tunnel Tests of Parent-Pallet deployment
•Aerodynamic Shape of Pallet and Separation Mechanism
Design Pallet Deployment Mechanism
Fabricate Pallet and Deployment Mechanism
Electronic Systems Group
Pallet with Deployment Mechanis
Mar
April
May

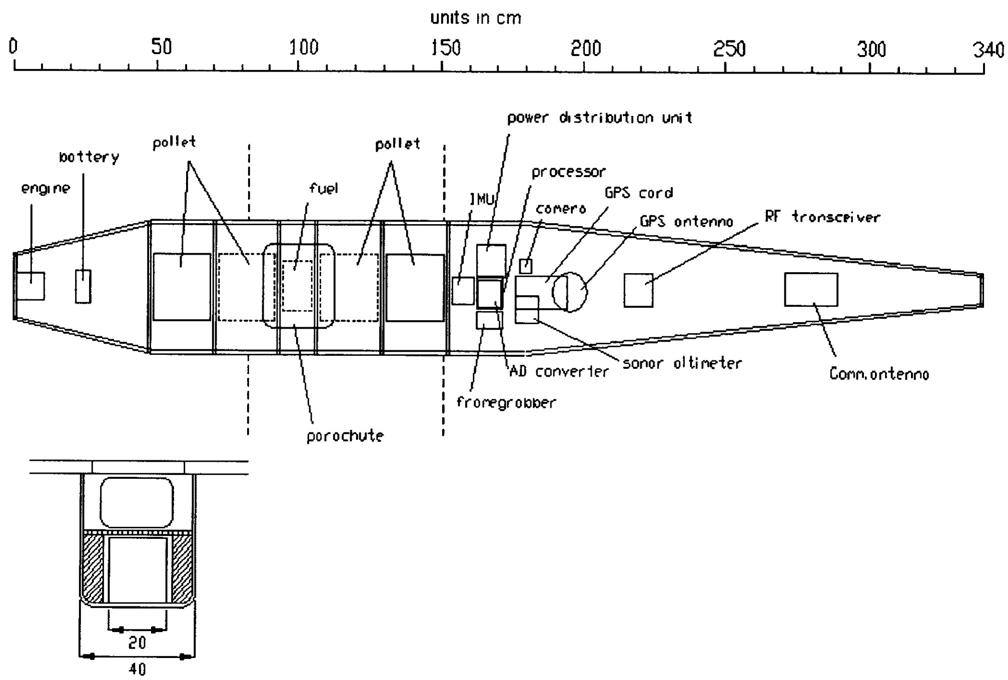
Spring –1999



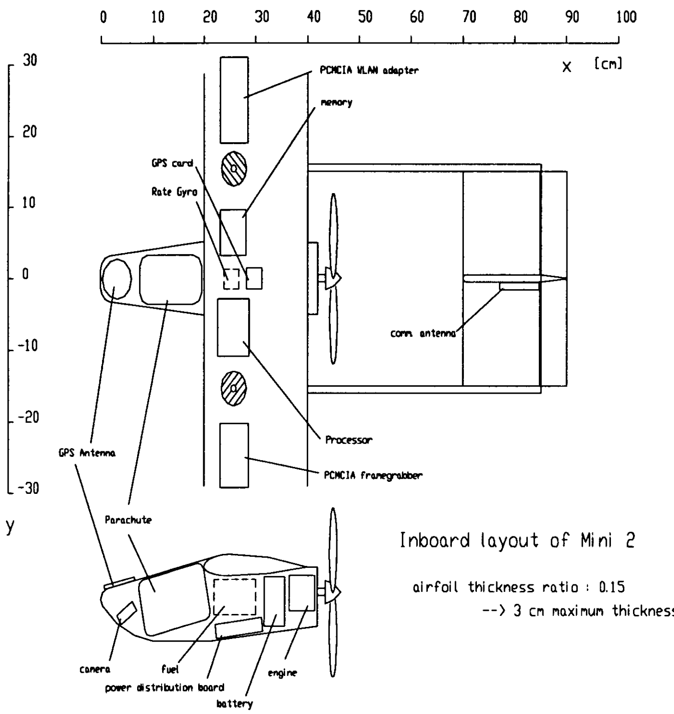
ELECTRONIC SYSTEMS GROUP
Determine GS Computer Hardware
Determine GS Comm Hardware
Determine Parent Vehicle Computer Hardware
Determine MINI Vehicle Computer Hardware
Determine Parent Vehicle Communication Hardware
Determine MINI Vehicle Communication Hardware
Determine Parent Vehicle Sensor Package
Determine MINI Vehicle Sensor Package
Acquire HW
Acquire HW
Acquire HW
Acquire HW
Acquire HW
Acquire HW
Acquire HW
Integrate GS Computer With Comm HW
Integrate Parent Computer With Comm HW
Integrate Child Computer with Comm HW
Bench Test Communication Between GS - Parent HW
Bench Test Communication Between Parent - MINI- HW
Integrate Parent Computer With Sensor Package
Integrate Child Computer with Sensor Package
Bench Test Transfer of Sensor Data From MINI-Parent-GS
Preliminary Design of the MINI Vehicle Electronics Package
Deliver Bench Tested Parent Electronics.
Preliminary Design of the Parent Vehicle Electronics Package
Deliver Bench Tested MINI Electronics.
Vehicle Group
Mar
April
May

Spring -1999

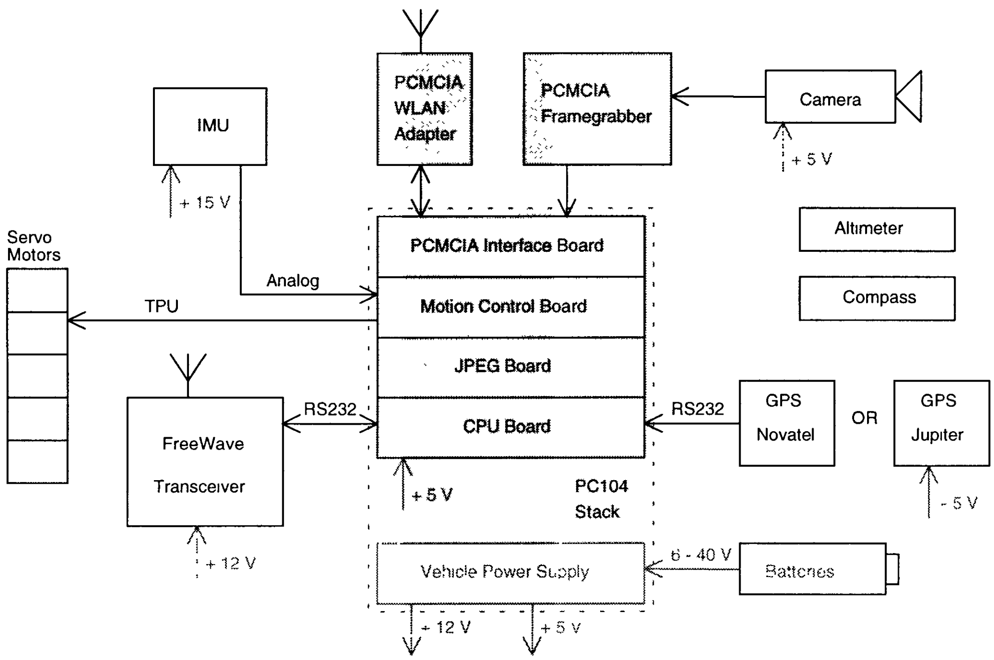
APPENDIX D -Vehicle Inboard Profiles and Avionics Architecture



Parent inboard layout (Courtesy of Sanghyuk Park)



Mini inboard layout (Courtesy of Sanghyuk Park)



Parent avionics architecture based on PC104 computer (Courtesy of Alexander Omelchenko)