A Small Unmanned Aerial Vehicle for Military and Civilian Applications

by

David R. Gordon

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

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Signature of Author: ____________________
Department of Aeronautics and Astronautics
May 9, 1997

Certified by: ____________________
Charles Boppe
Senior Lecturer, Department of Aeronautics and Astronautics
Thesis Supervisor

Certified by: ____________________
Stanley Weiss
Visiting Professor of Aeronautics and Astronautics
Thesis Supervisor

Accepted by: ____________________
Jaime Peraire
Associate Professor of Aeronautics and Astronautics
Chairman, Departmental Graduate Committee

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Abstract

The top-level design of a small unmanned aerial vehicle (S-UAV) was generated using many valuable systems engineering tools and practices. The design sought to serve as both a "stepping stone" to smaller UAVs which are beyond present-day technology, and as a useful vehicle for a variety of military and civilian applications. A market assessment was performed to determine the needs of potential civilian customers. An analysis of requirements was used to translate these customer needs into a set of technical requirements through the use of a Quality Function Deployment matrix. A design concept was generated using several systems engineering tools, including a Functional Flow Diagram which was synthesized into two levels of Schematic Block Diagrams, trade studies, and an architectural variant analysis. Finally, detailed design was begun on the individual subsystems of which the system as a whole is composed.

The final S-UAV configuration is a ducted fan 18 cm in diameter, weighing 1.4 kg; it is capable of hovering and flying with a forward speed between 0 and 30 km/hr (in still air). It is powered by a small internal combustion engine, and has an endurance of 25 minutes and a range between one and three kilometers. The payload is an imaging camera, which is capable of transmitting compressed images at rates up to 30 frames/second to the ground station via a wireless modem. Other on-board instrumentation includes a Global Positioning System unit, an inertial measurement unit, two sonar rangers and two 486 processors. It is controlled from the ground station (which is facilitated by real-time image transmission), but has the capability of autonomously detecting and avoiding obstacles in its path. Once in production, the total acquisition cost of the vehicle itself is estimated at $10,000.

Thesis Supervisor: Charles Boppe
Title: Senior Lecturer, Department of Aeronautics and Astronautics

Thesis Supervisor: Stanley Weiss
Title: Visiting Professor of Aeronautics and Astronautics

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Of course, this was not a team of one, and I would like to thank my teammates Arnaldo Leon and Young-Rae Kim. Only together could this design have been completed.

Finally, my eternal thanks go out to my family and to Tanya, for supporting me and keeping me cheerful over the past year.

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Section 1: Introduction and Project Process

The concept of a small unmanned aerial vehicle (UAV) has been proposed often in recent years as a military project, but rarely with civilian applications in mind. For reasons of stealth, these military studies have focused primarily on the design of micro-UAVs, with wingspans on the order of a few inches. At present, however, the technology required to construct a UAV of this size has not been fully realised. This project seeks to bridge the gap between existing (full-size) UAVs and micro-UAVs. Figure 1.1 (based on a figure in Davis) illustrates the scale of the UAV proposed for this project, as well as the scales of existing and previously proposed UAVs.

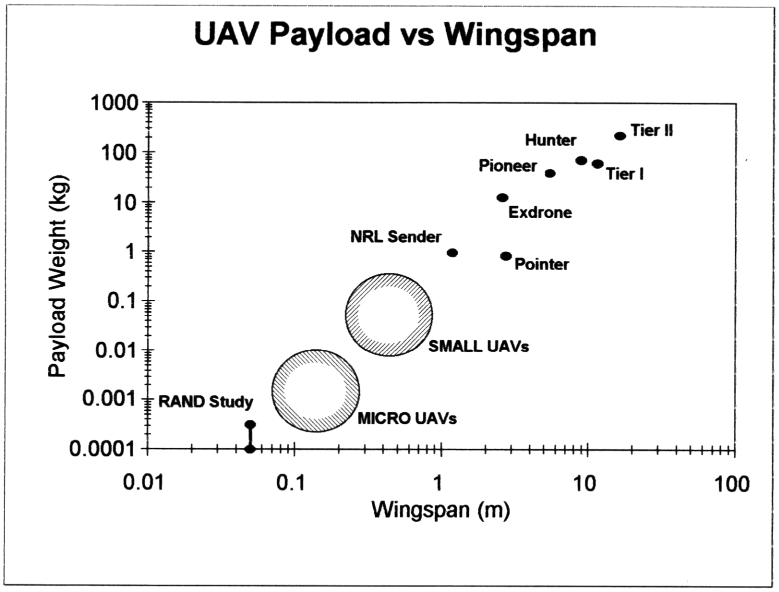


Figure 1.1: Existing and proposed UAV size envelopes

This project was inspired by the micro-UAV work currently being performed at the Massachusetts Institute of Technology's Lincoln Laboratory. The focus of the Lincoln Lab project is a UAV with a wingspan of three inches. This micro-UAV would be fitted with an imaging sensor, and would be used for military surveillance missions. The Lincoln project is partly in response to a desire by the Defense Advanced Research Projects Agency (DARPA) to develop a micro air vehicle capable of performing a useful military mission at an affordable cost. However, there are still several technological hurdles which need to be overcome, such as achieving sufficient battery energy density, before a UAV on this scale may be put into use.

Occupying the smallest wingspan and weight region of figure 1.1 are the potential UAVs proposed in the documented briefing, "Future Technology-Driven Revolutions in Military Operations; Results of a Workshop," published by RAND. In late 1992, RAND conducted a workshop for the Advanced Research Projects Agency (ARPA) in which the military application of micro-UAVs (on the scale shown in figure 1.1) was discussed. The briefing explores the concept of the "fly-on-the-wall" UAV; a vehicle so small that it would be capable of literally attaching itself to a wall, unnoticed, and gathering information. The report also proposes a "wasp" variant of micro-UAV, which would be designed to inflict localized damage to equipment. UAVs on this scale are at present still very theoretical.

The process by which the project — the development of a viable top-level design of a small UAV — progressed is shown in figure 1.2:

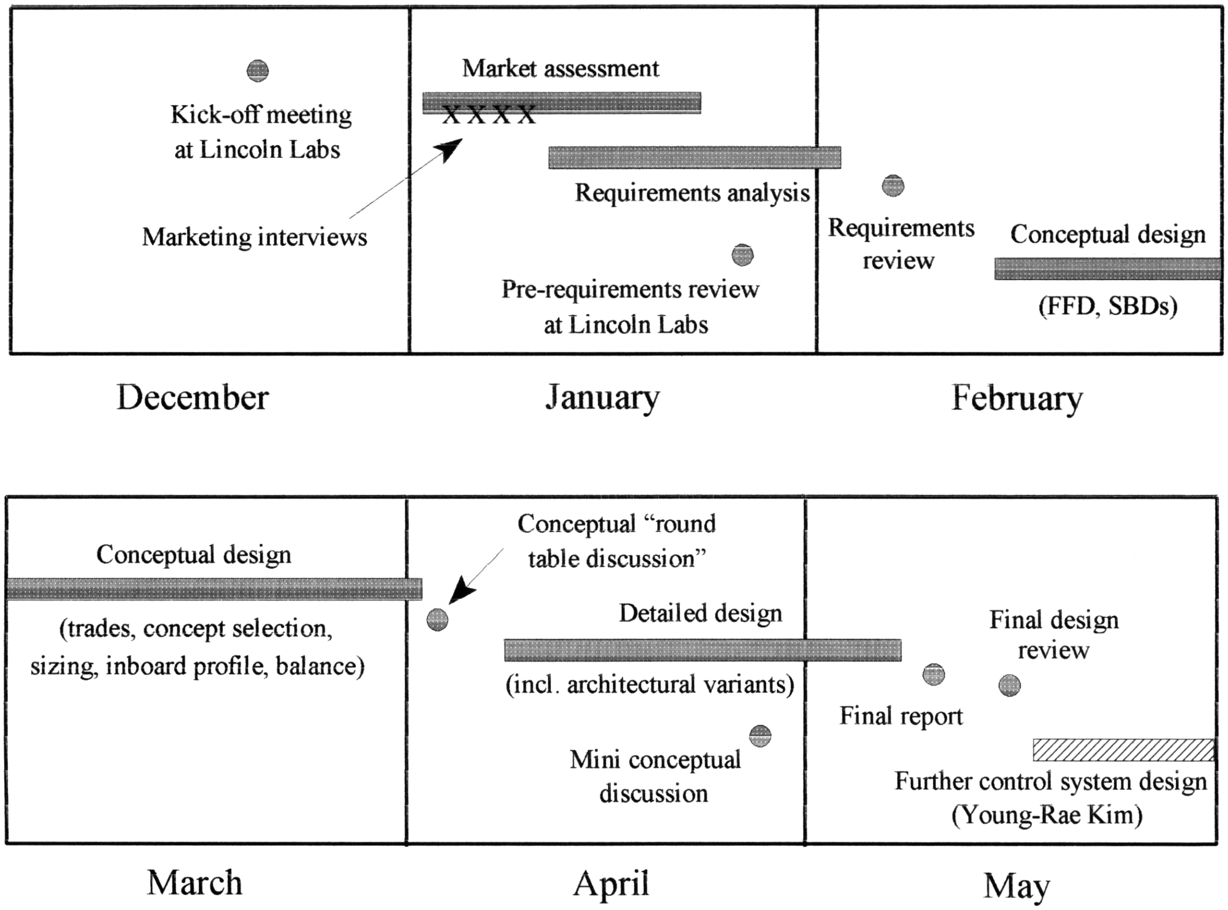


Figure 1.2: Project process and time frame

The project was completed in what was essentially a four month period, from January to April 1997 inclusive. It began with an assessment of the potential civilian market for a small UAV, and an analysis of the requirements which would drive the design. Following a review of the findings thus far, conceptual design was begun, in which the configuration, size and architecture of the vehicle was determined. A discussion was organized in order to obtain feedback from a few experts in various fields, and to review the design concept. Finally, a month of detail work resulted in a top-level design for a small UAV, which was characterized in the individual theses of the team members and presented in a final design review.

Section 2: Potential Applications and Market Assessment

Before the design process can begin, a sense must be gained of what potential markets exist for the small UAV (henceforth denoted as S-UAV), and what those markets would require of the design. This section will discuss some possible civilian applications for the S-UAV, and the feedback received from the market assessment which was performed.

Initially, the design team brainstormed a list of possible missions which could be performed by a UAV in the size range indicated in figure 1.1. A list of about one hundred such missions was generated; these missions were then classified into nine broad categories: surveillance and law enforcement, facility and infrastructure inspection, news and sports coverage, search and rescue, environmental studies, mapping and surveying, parcel delivery and communications, hobby and advertising, and planetary exploration. The latter three mission categories were discarded as being impractical, being incompatible with Lincoln Laboratory and DARPA objectives, and/or having too limited a market. The others, which were deemed suitable for further assessment, will be discussed individually below.

Surveillance and Law Enforcement

Small UAVs could be used as flying security cameras, or as tracking devices by police forces. Potentially, some missions for which full-sized police helicopters are currently used could be performed by a small UAV. The principal benefits of using a small UAV in this type of role are low observability, good vantage point, and reduced risk and cost compared to manned operations. Very small UAVs could even be used for indoor situations.

The MIT Campus Police were contacted regarding the requirements for a UAV to be useful in a law enforcement role. Hovering capability, some type of remote control and a video system were thought to be characteristics which would be required. Depending on the specific mission, long range capability and/or an infrared camera might be desired. Above all, cost is a driving factor in determining the suitability of the UAV to a police force, particularly to a small department. In addition, there is serious concern regarding liability in the event of a crash or loss of control, since these UAVs would be used in an urban setting.

Facility and Infrastructure Inspection

Large structures, such as skyscrapers or bridges, can be difficult and dangerous to inspect for corrosion or damage. A small UAV, equipped with a high-quality visual imager, could potentially be used to perform such inspections, resulting in a cost savings as well as a vast increase in worker safety.

A representative from Aerial Buckets, a boom truck dealer, was contacted concerning possible inspection uses for a small UAV. Currently, bridge inspection is performed using a truck with a three-part boom (to reach out, down, and under). Not only does this truck cost $1500 per day to rent, but the inspector is put at risk, being in a bucket at the end of the boom. If the inspection were performed via a remote camera on a small UAV, it would save both the rental of the heavy equipment and the jeopardy of the worker. In this role, some of the important requirements of the UAV would be the capability to hover, excellent quality imaging, ease of operation, and low cost.

News and Sports Coverage

Television networks are always attempting to gain a better vantage point for their cameras, in order to render their coverage of events more interesting to the public. Witness the Olympic Games: small cameras have been placed in bobsleds, in the helmets of skiers, in the boats of rowers, and on and on. News crews, as well, are always searching for a better angle, even making use of full-sized helicopters when the budget allows. A small UAV could provide a new vantage point; one with the flexibility to “follow the action,” no matter how a situation develops. In addition, UAVs could be used as an inexpensive alternative to full-sized helicopters for traffic reporting.

According to Jeff Brown, president of WBZ-AM News Radio (Metro Traffic), the primary concern of news stations with regard to operating a UAV in an urban setting is liability in the event of a crash. The UAV must be small enough, and light enough, that crash liability is reduced to a negligible level. Video transmission would be a requirement of the UAV design, as would the capability to hover and ease of operation. If the images captured by the UAV are to be used for television broadcasting, they must be of a reasonably high quality — although news camera crews are willing to sacrifice some image quality for a better vantage point. Also, as with all the civilian markets, cost is a driving factor.

Search and Rescue

In this role, a small UAV could be used to perform the "search" segment of a search-and-rescue operation. It could transmit still photographs to the ground station until the target of the search is identified, at which time the rescue crew could proceed to the correct location. Using several UAVs, a larger area could be covered more quickly, and for a lower cost, than with a conventional helicopter. It was envisioned that these UAVs could be used by search teams from the Coast Guard to ski patrols. In a different form, a UAV could also be used to send into burning buildings and search for trapped people.

Interest was expressed by ski patrols in the use of small UAVs to aid their search and rescue operations — particularly in post-avalanche situations, when manned searching is very risky. Cost, once again, is a critical consideration. A long range and the ability to fly in adverse weather conditions are other important requirements of the design. Operations which are on a larger scale, such as those performed by the Coast Guard, would require *very* long range and high endurance — this may be beyond the capability of a small UAV.

Environmental Studies

The payload of a small UAV is certainly not restricted to an imaging camera. Environmental sensors of any kind could be installed, and the UAV used to collect scientific data. It could sample air quality, measure the composition of smokestack emissions, or determine pressure and temperature variations with altitude. It could be used for the assessment of hazardous environments, such as those following chemical or nuclear accidents.

For meteorological studies, long range is essential. According to the MIT Department of Earth, Atmospheric and Planetary Sciences, meteorological studies cover a range of 10 km horizontally and 5 km vertically. For more localized studies, this becomes less of an issue. In order to be capable of taking an adequate amount of data in a particular area, the UAV would need to fly slowly, and be able to process data quickly. As well, it could not itself produce any emissions or exhaust which might contaminate the sensor readings. Small size is not a requirement for this role.

Mapping and Surveying

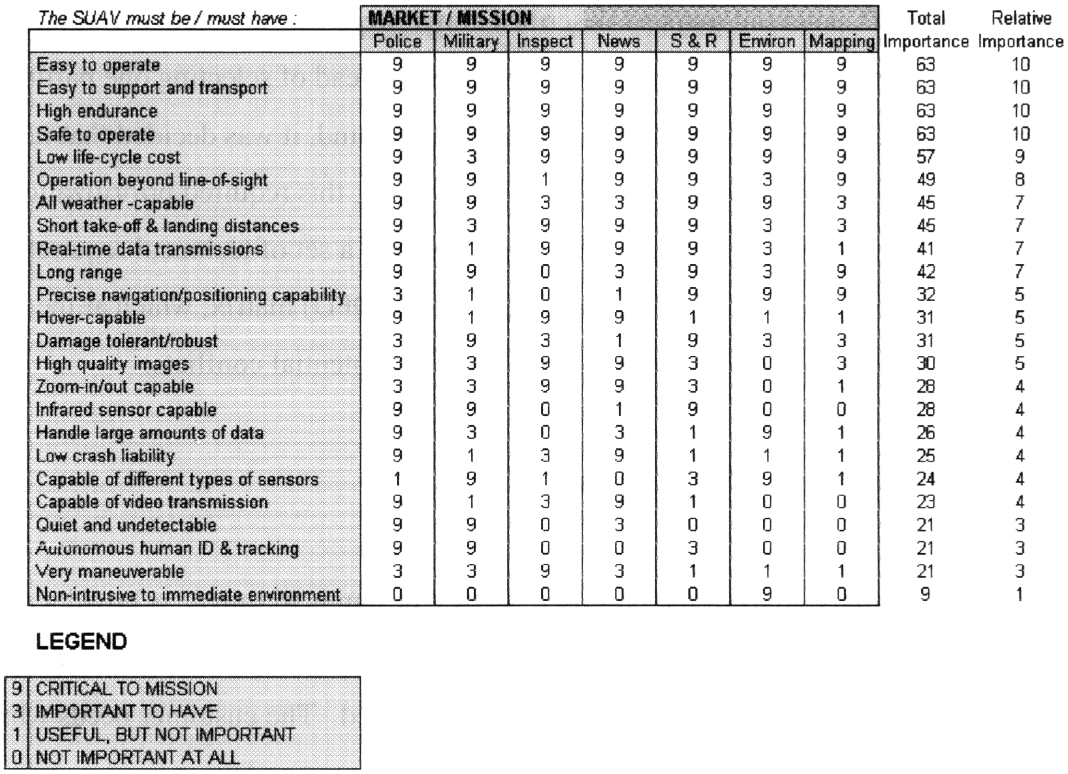
Perhaps the most direct extension of the military role performed by Lincoln Lab's micro-UAVs into the civilian market is in mapping and surveying. A UAV could fly over an area of interest and take pictures, which would be collected by the ground station for analysis. It could be used to survey potential construction areas, archeological sites, or even for deep-sea fish spotting. Because of its similarity to the military scenario, this application will not be considered a distinct mission for the remainder of this thesis.

Section 3: Requirements Analysis

The market assessment described in the previous section resulted in a list of top-level customer needs. These govern the operational and performance characteristics which would be required of the small UAV in order to be useful to the potential customers. Translation of these broad needs into more specific engineering requirements is the goal of a requirements analysis. In this case, the requirements analysis was performed in two steps. First, all the different and diverse needs of the six potential markets described above were consolidated, and prioritized in order to satisfy the largest number of customers possible. Instead of selecting one particular mission and designing the S-UAV with only that mission in mind, it was decided that it would be more economically sound to design to a broad total market; this required prioritization and trade-offs. Second, these customer needs were translated into a set of technical requirements through the construction of a Quality Function Deployment (QFD) matrix, which at the same time prioritized those technical requirements and identified potential conflicts.

3.1 Prioritization of Customer Needs

One of the primary goals of the proposed S-UAV design is to satisfy as broad a range of customers as possible. To this end, the requirements analysis did not focus on one particular mission scenario; rather, all potential missions were considered. The customer needs which were revealed as a result of the market assessment were integrated and prioritized, in order to determine which needs were associated with the most missions, and hence which were the most important. Figure 3.1 shows the method by which these needs were ranked. Listed down the left of the table are customer needs, and across the top are the different potential markets, as outlined in section 2, above. Included as well is a column for a military surveillance or reconnaissance mission, such as is the focus of the Lincoln Laboratory's micro-UAVs. In the table are numbers which correspond to the importance of the particular need to the particular mission; a nine indicating critical importance, a three indicating moderate importance, a one indicating usefulness, and a zero indicating no importance. The seemingly disproportional difference between a nine and a three is to serve as a discriminator between those needs which are truly critical to the vehicle's usefulness and those which are only of moderate importance. These numbers are then totalled on the right of the table, and then normalized to a weight out of ten.



The SUAV must be / must have :	**MARKET / MISSION**							Total	Relative
	Police	Military	Inspect	News	S & R	Environ	Mapping	Importance	Importance
Easy to operate	9	9	9	9	9	9	9	63	10
Easy to support and transport	9	9	9	9	9	9	9	63	10
High endurance	9	9	9	9	9	9	9	63	10
Safe to operate	9	9	9	9	9	9	9	63	10
Low life-cycle cost	9	3	9	9	9	9	9	57	9
Operation beyond line-of-sight	9	9	1	9	9	3	9	49	8
All weather -capable	9	9	3	3	9	9	3	45	7
Short take-off & landing distances	9	3	9	9	9	3	3	45	7
Real-time data transmissions	9	1	9	9	9	3	1	41	7
Long range	9	9	0	3	9	3	9	42	7
Precise navigation/positioning capability	3	1	0	1	9	9	9	32	5
Hover-capable	9	1	9	9	1	1	1	31	5
Damage tolerant/robust	3	9	3	1	9	3	3	31	5
High quality images	3	3	9	9	3	0	3	30	5
Zoom-in/out capable	3	3	9	9	3	0	1	28	4
Infrared sensor capable	9	9	0	1	9	0	0	28	4
Handle large amounts of data	9	3	0	3	1	9	1	26	4
Low crash liability	9	1	3	9	1	1	1	25	4
Capable of different types of sensors	1	9	1	0	3	9	1	24	4
Capable of video transmission	9	1	3	9	1	0	0	23	4
Quiet and undetectable	9	9	0	3	0	0	0	21	3
Autonomous human ID & tracking	9	9	0	0	3	0	0	21	3
Very maneuverable	3	3	9	3	1	1	1	21	3
Non-intrusive to immediate environment	0	0	0	0	0	9	0	9	1

LEGEND

9	CRITICAL TO MISSION
3	IMPORTANT TO HAVE
1	USEFUL, BUT NOT IMPORTANT
0	NOT IMPORTANT AT ALL

Figure 3.1: Prioritization of customer needs

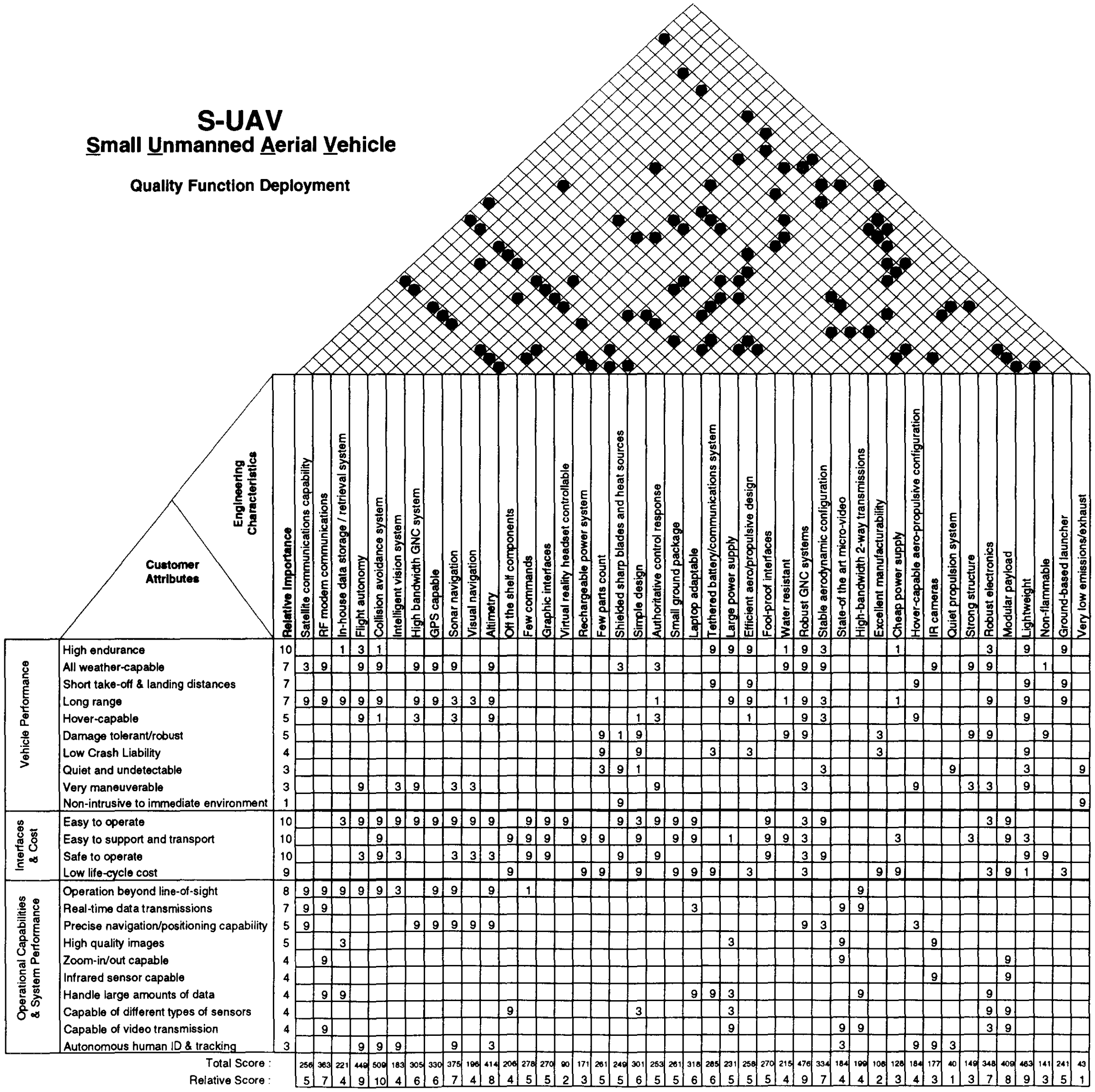
It is important to note that the need for a basic imaging camera does not appear in figure 3.1. Of the potential missions listed above and described in section 2, only environmental studies would remain feasible if the S-UAV did not possess the ability to capture visual images. Because this type of imaging is so central to the operation of the vehicle, the requirement for a visual camera was considered a constraint, and was kept separate from the other customer needs for the purposes of the requirements analysis. The needs listed in figure 3.1 represent characteristics which are "tradeable" regardless of their importance; visual imaging capability simply cannot be among them.

From figure 3.1, it is clear that operational considerations — particularly ease and safety — are most important for the S-UAV, as well as total cost. These derived weightings of the customer needs were then used to determine a prioritized set of technical requirements, using a Quality Function Deployment matrix.

3.2 Quality Function Deployment

A Quality Function Deployment matrix is a tool which serves to translate a set of broad, top-level customer needs into a set of more specific engineering requirements which can be used for design purposes. In addition, it identifies important conflicts between these technical requirements, and it allows for traceability back from the design to the original needs of the customer.

The QFD matrix for the S-UAV is shown in Figure 3.2. Down the left side of the matrix are the customer requirements, grouped into the three categories of vehicle performance, interfaces & cost, and operational capabilities & system performance. Beside each need is its relative importance, which was derived above (Prioritization of Customer Needs). Across the top of the matrix is a list of technical requirements which address one or more of the customer needs. In the body of the matrix are weightings which quantify how well a particular customer need is addressed by a particular technical requirement. The same 9-3-1 scale is used as was used previously; a nine indicates a very strong correlation, a three indicates a moderate correlation, and a one indicates a weak correlation. Each weighting is then multiplied by the importance of its customer need, and each column is summed at the bottom of the matrix. This results in a ranking of the technical requirements, which is normalized using a base of ten. In



S-UAV

Small Unmanned Aerial Vehicle

Quality Function Deployment

Engineering Characteristics

	Customer Attributes	Relative Importance	Satellite communications capability	RF modem communications	In-house data storage / retrieval system	Flight autonomy	Collision avoidance system	Intelligent vision system	High bandwidth GNC system	GPS capable	Sonar navigation	Visual navigation	Altimetry	Off the shelf components	Few commands	Graphic interfaces	Virtual reality headset controllable	Rechargeable power system	Few parts count	Shielded sharp blades and heat sources	Simple design	Authoritative control response	Small ground package	Laptop adaptable	Tethered battery/communications system	Large power supply	Efficient aero/propulsive design	Fool-proof interfaces	Water resistant	Robust GNC systems	Stable aerodynamic configuration	State-of the art micro-video	High-bandwidth 2-way transmissions	Excellent manufacturability	Cheap power supply	Hover-capable aero-propulsive configuration	IR cameras	Quiet propulsion system	Strong structure	Robust electronics	Modular payload	Lightweight	Non-flammable	Ground-based launcher	Very low emissions/exhaust
Vehicle Performance	High endurance	10			1	3	1																		9	9	9		1	9	3				1					3		9		9	
	All weather-capable	7	3	9		9	9		9	9	9		9							3		3							9	9	9						9		9	9			1		
	Short take-off & landing distances	7																							9		9									9						9		9	
	Long range	7	9	9	9	9	9		9	9	3	3	9									1				9	9		1	9	3				1					9		9		9	
	Hover-capable	5				9	1		3		3		9								1	3					1			9	3					9						9			
	Damage tolerant/robust	5																	9	1	9								9	9				3					9	9			9		
	Low Crash Liability	4																	9		9				3		3							3								9			
	Quiet and undetectable	3																	3	9	1										3							9				3			9
	Very maneuverable	3				9		3	9		3	3										9								3						9			3	3		9			
	Non-intrusive to immediate environment	1																		9																									9
Interfaces & Cost	Easy to operate	10			3	9	9	9	9	9	9	9	9		9	9	9			9	3	9	9	9				9		3	9									3	9				
	Easy to support and transport	10					9							9	9	9		9	9		9		9	9		1		9	9	3					3				3		9	3			
	Safe to operate	10				3	9	3			3	3	3		9	9				9		9						9		3	9											9	9		
	Low life-cycle cost	9												9				9	9		9		9	9	9		3			3				9	9					3	9	1		3	
Operational Capabilities & System Performance	Operation beyond line-of-sight	8	9	9	9	9	9	3		9	9		9		1																		9												
	Real-time data transmissions	7	9	9																				3								9	9												
	Precise navigation/positioning capability	5	9						9	9	9	9	9																	9	3					3									
	High quality images	5			3																					3						9					9								
	Zoom-in/out capable	4		9																												9									9				
	Infrared sensor capable	4																																			9				9				
	Handle large amounts of data	4		9	9																			9	9	3							9							9					
	Capable of different types of sensors	4												9							3					3														9	9				
	Capable of video transmission	4		9																						9						9	9							3	9				
	Autonomous human ID & tracking	3				9	9	9			9		3																			3				9	9	3							
	Total Score :		256	363	221	449	509	183	305	330	375	196	414	206	278	270	90	171	261	249	301	253	261	318	285	231	258	270	215	476	334	184	199	108	128	184	177	40	149	348	409	463	141	241	43
	Relative Score :		5	7	4	9	10	4	6	6	7	4	8	4	5	5	2	3	5	5	6	5	5	6	6	5	5	5	4	9	7	4	4	2	3	4	3	1	3	7	8	9	3	5	1

Figure 3.2: Quality Function Deployment for the S-UAV

the triangular “roof” which sits atop the matrix, potential conflicts between requirements are identified.

When the relative scores of the technical characteristics for the S-UAV are calculated, six particular requirements receive scores of eight or greater. These most important technical requirements are:

Requirement	*Score*
Collision avoidance system	10
Robust GN&C system	9
Lightweight	9
Flight autonomy	9
Altimetry	8
Modular payload	8

As can be seen, four of these six top scoring requirements deal with guidance, navigation and control. Also scoring highly are lightweight, for reasons which are perhaps obvious, and modular payload, which is very important if multiple customers, with different payload needs, are to be accommodated.

In the QFD matrix, a few potential conflicts were identified which occurred between two highly-rated requirements. The requirement for light weight conflicts with the capability for modular payload, as modular interfaces represent a compromise rather than an idealization; thus, weight might not be optimized. “Robust electronics” scored a seven in the QFD matrix, making it one of the top ten technical requirements — it may also conflict with the need for light weight, as any kind of redundancy will add weight to the vehicle. Another requirement which may result in problems is “simple design” (with a score of six). This conflicts with many of the high-scoring requirements for complex systems, such as a collision avoidance system or flight autonomy. The conflicts which were identified in the QFD matrix, particularly the important ones described above, were examined in the trade studies which form an integral part of conceptual design.

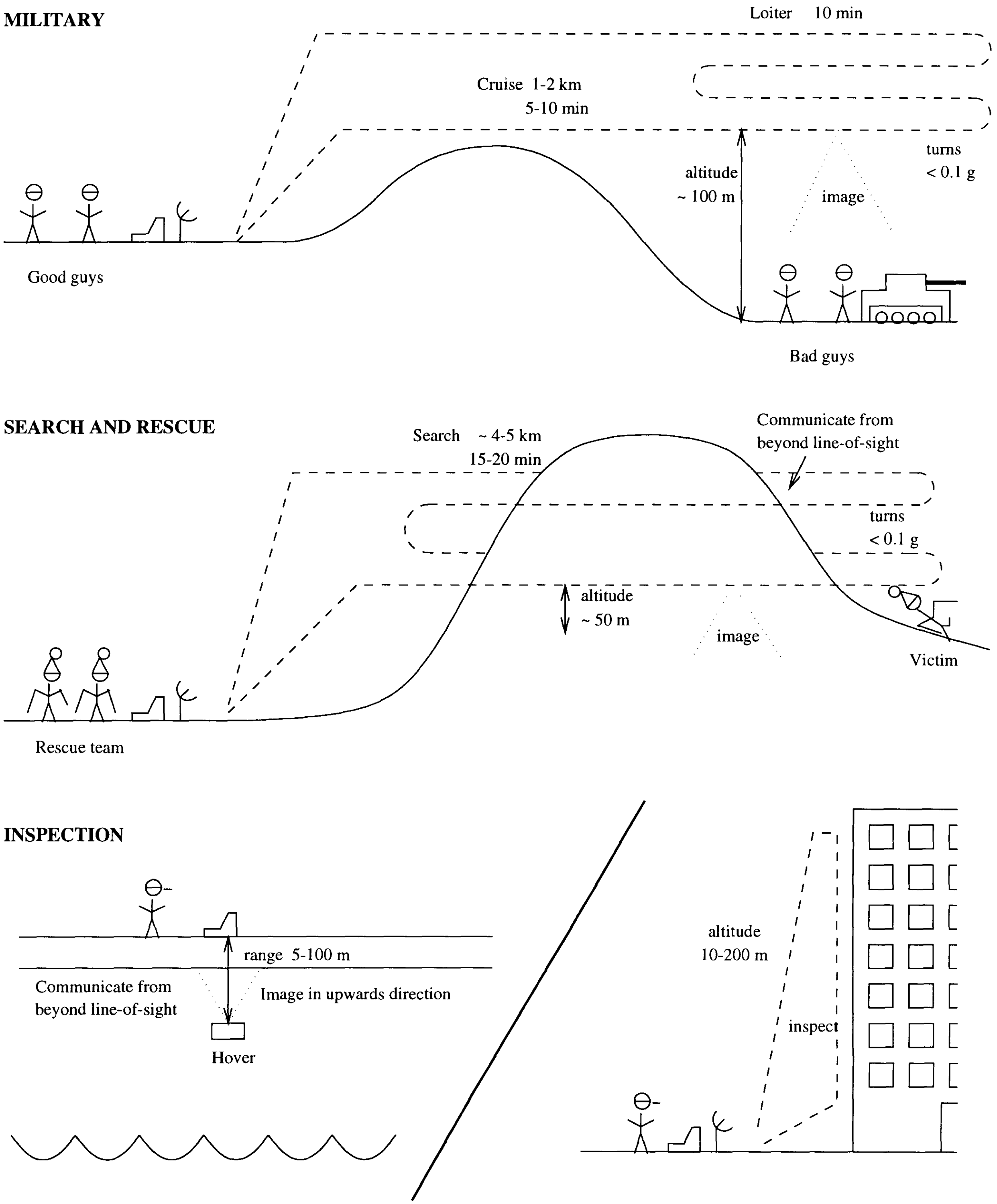
Section 4: Design Concept

In the conceptual stage of the design process, the vehicle itself begins to take shape. It is where the requirements derived in the previous section begin to coalesce into a UAV of a specified size and weight, and comprising specified subsystems. Conceptual design begins with the definition of missions and functions for the vehicle, followed by the translation of those missions into required subsystems and overall size, and closes with the synthesis of these previous steps into a top-level S-UAV design.

4.1 Mission Scenarios and Point Performance Requirements

To begin the process of conceptual design, it is important to gain a sense of the specific performance requirements of the vehicle within the context of each application which was envisioned in section 2. The process of graphically outlining mission scenarios is both an extension and a synthesis of sections 2 and 3; we can see at a glance what mission the vehicle is performing, and what sort of range, altitude and endurance is required of it. Of particular importance are point performance requirements — performance characteristics which may be required of the vehicle only at a certain point in the mission. For example, it may become clear through a graphical mission profile that the S-UAV needs to perform a high-g turn during the mission, or needs to climb rapidly, or any number of point performance requirements which may not otherwise have surfaced in a general requirements analysis.

For the S-UAV, mission profiles were generated for six missions: the military or DARPA mission, law enforcement, inspection, news coverage, search and rescue, and environmental studies. The surveying mission was taken to be identical to the military mission, differing only in the target of the images taken. These mission scenarios are shown in figures 4.1 and 4.2.

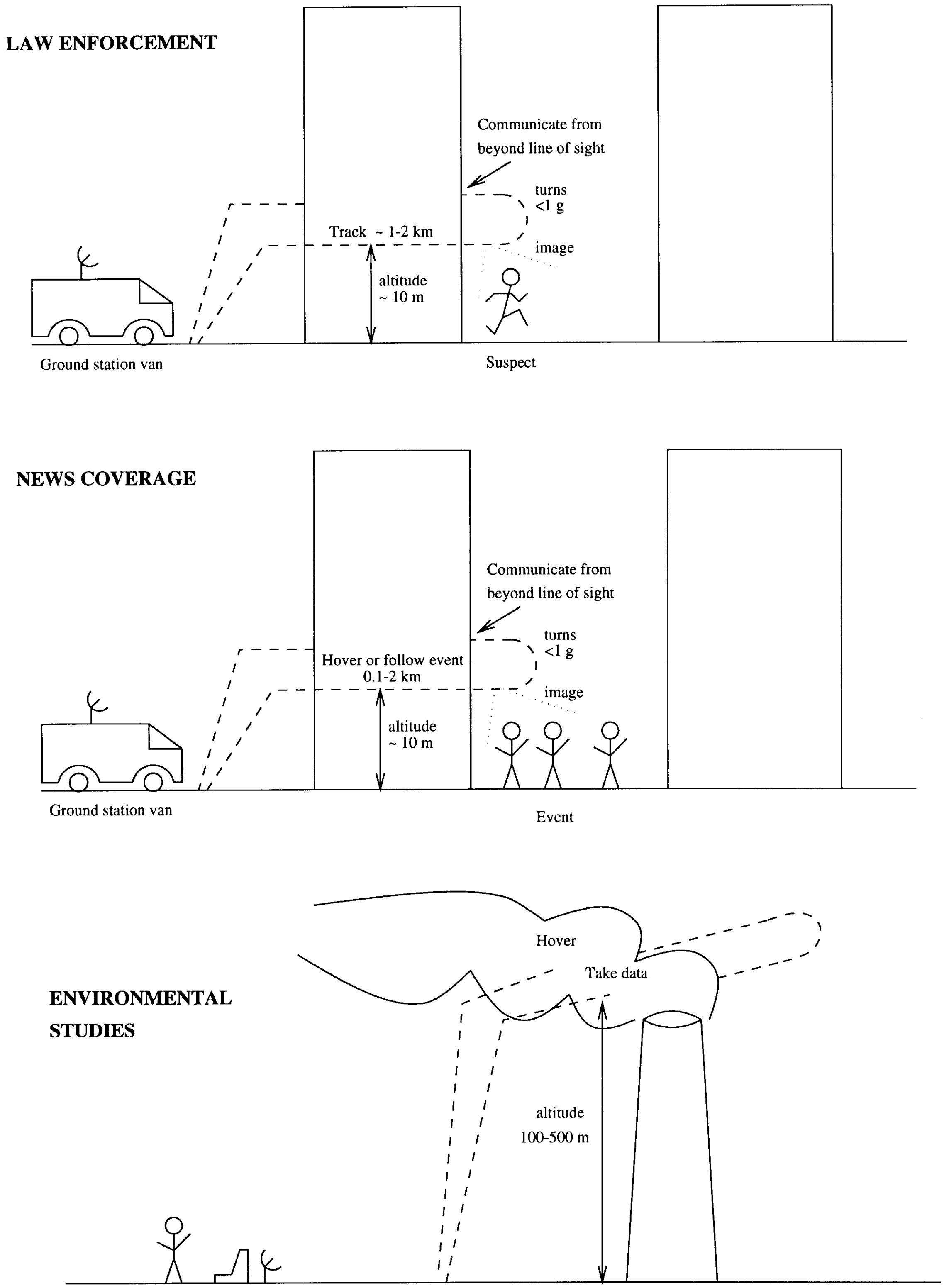


MILITARY

SEARCH AND RESCUE

INSPECTION

Figure 4.1: S-UAV mission profiles 1



LAW ENFORCEMENT

NEWS COVERAGE

ENVIRONMENTAL STUDIES

Figure 4.2: S-UAV mission profiles 2

As can be seen, few point performance requirements would be encountered by the S-UAV. Hovering capability and communication beyond line-of-sight are clearly the most important, being required in several of the potential missions. In addition, the tracking of a fleeing suspect or the following of a newsworthy event might require a reasonably high forward velocity and possibly a high-g turn, in the cases of law enforcement or news coverage. A search and rescue mission could also require a reasonable velocity, in order to locate its target quickly. These mission profiles can then be used later in the design, to ensure that the performance requirements (point or otherwise) are met.

4.2 Functional Analysis

The next step in the conceptual design process is to examine the specific functions of the vehicle, without any particular scenario in mind. A Functional Flow Diagram (FFD) is a graphical means of organising the functions that are to be performed by the system into a clear sequence. The FFD for the S-UAV is shown in figure 4.3. Time flows from left to right. Functions (enclosed in rectangles) which are to be performed in parallel are stacked vertically; an "and" symbol preceding them indicates that both are to be performed, while an "or" indicates only one is to be performed.

As may be expected, the majority of the functions to be performed by the system occur during flight; however, there are a few important functions which are required while the S-UAV is on the ground. It is important to note that, in general, each "branch" of functions which occur during flight is to be continually repeated. For example, the vehicle acquires obstacle data, then provides collision avoidance capability, then acquires new obstacle data, an so on until it is shut down.

A Functional Flow diagram can be a useful tool for generating variants of the system, in order to ensure that the design effort does not focus in on one configuration, to the exclusion of all others, so early in the design process. Variants can be generated by changing the order of

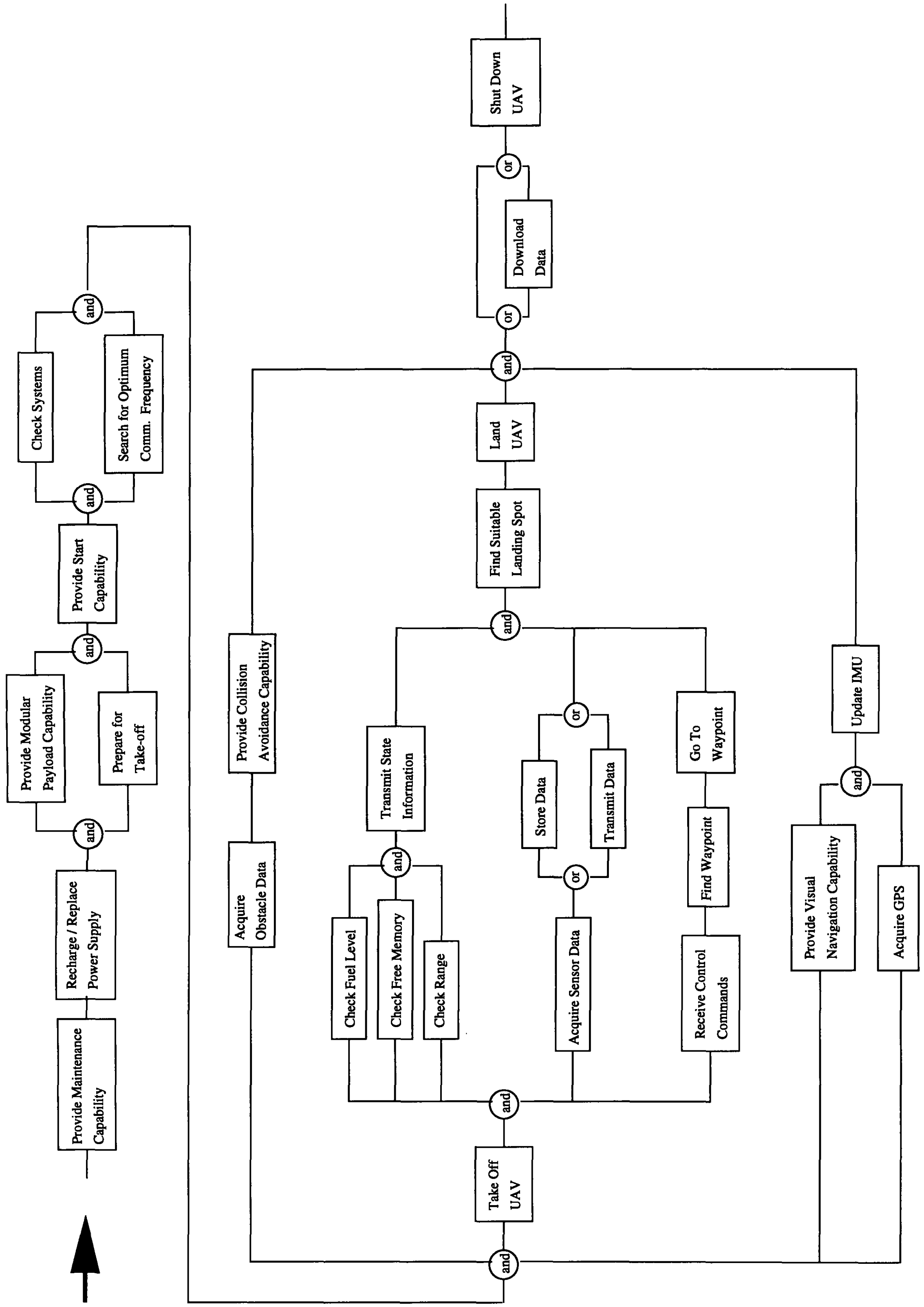


Figure 4.3: Functional Flow Diagram for the S-UAV

functions, or by performing functions in parallel which were previously in series, or changing the positions of "and" and "or" gates. For example, the function "search for optimum communication frequency" may be performed continually in flight, rather than simply before take-off; thus, the function box might be placed in parallel with the in-flight functions. Once a preferred functional flow diagram is generated, the subsystems which are required to perform all the necessary functions can be identified.

4.3 Subsystems and Interfaces

The next phase of conceptual design involves the identification of the subsystems that are to make up the system as a whole, and of the interfaces between those subsystems. Perhaps the optimum method by which to identify the subsystems is synthesis of the functional flow diagram. Each function contained in the FFD requires a particular subsystem or subsystems to be present on the vehicle; by analysing each function in turn, a complete list of necessary subsystems can be developed.

Once the S-UAV subsystems have been identified, it must be determined what interfaces exist between them. This is the domain of the schematic block diagram. A schematic block diagram (SBD) illustrates the interfaces between subsystems, and identifies those interfaces according to type (signal, mechanical, hydraulic, etc.). The SBD that was developed for the S-UAV is shown in figure 4.4.

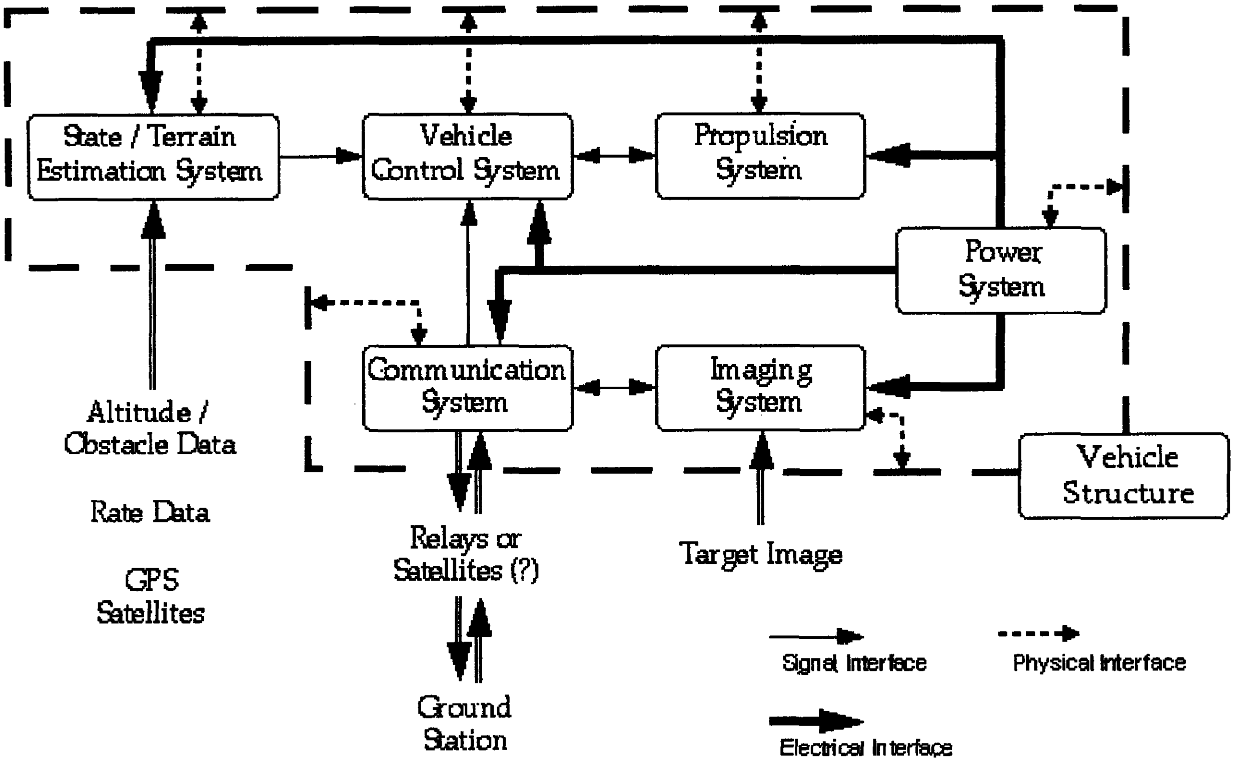


Figure 4.4: Schematic block diagram for the S-UAV

As can be seen, the S-UAV system as a whole comprises six subsystems, each of which plays a vital role in the operation of the vehicle. The state/terrain estimation system gathers information regarding the vehicle's position, motion and surroundings. It is responsible for providing collision avoidance capability — the most important technical requirement to surface as a result of the earlier requirements analysis (see section 3). The vehicle control system is responsible for the physical control of the S-UAV in flight; it maneuvers the vehicle in response to signals either from the estimation system (automatic control, such as for collision avoidance) or the communication system (manual control commands from the ground station). The communication system serves as the interface between the ground station and the other five subsystems. It receives commands by wireless radio signal from the ground station, and sends images and other data from the vehicle to the ground. These images are obtained by the imaging system (or alternately, as would be the case for environmental studies missions, the instrumentation payload), which fulfills the primary goal of the particular mission. The propulsion system generates and regulates the thrust required to keep the S-UAV aloft and perform the mission. Finally, the power system provides all the on-board components with electrical power, at the required voltage and current levels.

Another method of graphically representing the interfaces between subsystems is through the use of an N^2 diagram. An N^2 diagram is an N by N matrix (where N is the number of subsystems which make up the system as a whole), which details the interfaces which flow from subsystem to subsystem. The N^2 diagram for the S-UAV is shown in figure 4.5.

Comm. System	camera commands			control commands	
image data	**Imaging System**				
electrical power	electrical power	**Power System**	electrical power	electrical power	electrical power
			Estimation System	state / obstacle data	
position and speed data				**Control System**	throttle commands
				rotor RPM data	**Propulsion System**

Figure 4.5: S-UAV N^2 diagram

Interfaces flow in a clockwise direction; thus, "camera commands" are sent from the communication system to the imaging system, while "image data" is sent from the imaging system to the communication system.

A schematic block diagram can be used not only to decompose a system into subsystems, but also to decompose a subsystem into individual components. Constructing an SBD for each individual subsystem ensures that every component required of the vehicle as a whole is accounted for. Schematic block diagrams were constructed for each of the S-UAV's subsystems — this exercise resulted in the list of vehicle components which was used for the remainder of conceptual design (particularly for the inboard profile, detailed in section 4.5). The SBDs for the S-UAV subsystems are shown in section 5. Once a list of required components has been tabulated, preliminary vehicle size and weight estimates can be made. In addition, the weights of the interfaces themselves can be estimated, once an inboard profile (see below) has been generated. The process by which the interface weight was determined for the S-UAV is detailed in section 4.6.

4.4 Trade Studies and Concept Selection

In order to make decisions regarding the top-level design and configuration of any system, some kind of systematic method should be employed. For the S-UAV design, both trade studies and feasibility studies were used to select a concept and generate the preliminary size of the vehicle, although these two types of studies were not always in agreement.

It is clear from the mission scenarios presented in section 4.1 that the S-UAV requires the capability to hover; this point performance requirement surfaced in several of the mission profiles. A decision must be made, then, as to the hovering mechanism: a ducted fan, or a free rotor. To select between these two options, a trade study was performed as shown in table 4.1. Listed down the left of the table are those technical requirements derived from the Quality Function Deployment matrix which might be affected by the choice of hovering mechanism. Beside each is its relative importance determined by the QFD matrix. Listed under each option is a rating of the degree to which a given option would facilitate the corresponding technical requirement; a "1" denotes a weak correlation, while a "5" denotes a very strong correlation. For example, a free rotor would facilitate a lightweight vehicle (5) much more than a ducted fan (2), due to the added structure of the duct. These ratings are then multiplied by the importance of their technical requirements, and summed. The option with the higher total rating is the option which should be selected.

Technical Requirements	Score	Duct	No Duct
Collision avoidance system	10	5	2
Lightweight	9	2	5
Modular payload	8	3	4
Stable aerodynamic configuration	7	4	3
Simple design	6	3	4
Small ground package	5	5	2
Few parts count	5	2	5
Efficient aero/propulsive design	5	5	5
Authoritative control response	5	3	5
Shielded sharp blades and heat sources	5	5	1
Water resistant	4	4	3
Hover-capable aero-propulsive configuration	4	5	5
Strong structure	3	5	3
Excellent manufacturability	2	2	5
Quiet propulsion system	1	4	2
TOTAL		**294**	**284**

Table 4.1: Ducted fan vs free rotor trade study

In this particular case, the scores for the two arrangements are very similar; a difference of only three and a half percent separates them. This result is too close to facilitate a decision based solely on this study. To "break the tie," it was decided that the reduction in size which can be achieved using a ducted fan arrangement (see the thesis of team member Arnaldo M. Leon) merited implementing the ducted fan configuration for the S-UAV design.

This process was also applied to the type of engine to be used. Table 4.2 shows the trade study which was performed to determine the optimum choice of electric propulsion or gasoline propulsion. As can be seen, the two options once again have very similar scores, too much so to make a decision based solely on this trade study.

Technical Requirements	Score	Electric	Gas
High Endurance	10	1	5
Lightweight	9	2	5
Flight autonomy	9	4	3
Modular payload	8	4	4
Simple design	6	4	2
Tethered battery/communications system	6	5	1
Few parts count	5	4	1
Efficient aero/propulsive design	5	4	4
Authoritative control response	5	5	4
Shielded sharp blades and heat sources	5	4	4
Ground-based launcher	5	4	3
Large power supply	5	3	5
Water resistant	4	2	3
Off the shelf components	4	5	5
Hover-capable aero-propulsive configuration	4	5	3
Rechargeable power system	3	5	4
Non-flammable	3	5	3
Cheap power supply	3	5	3
Excellent manufacturability	2	5	2
Very low emissions/exhaust	1	5	1
Quiet propulsion system	1	5	1
TOTAL		**374**	**352**

Table 4.2: Electric vs gasoline trade study

In this case, the discriminator between the two choices is endurance. Although "high endurance" is included in the trade study itself, a minimum endurance time can be viewed more as a constraint than a requirement; the vehicle would become utterly useless for most of the missions envisioned in sections 2 and 4.1 if its endurance were less than fifteen minutes. By an analysis of engine power required for a certain weight of UAV, detailed in the thesis of team member Arnaldo M. Leon, it was found that for a vehicle in the size range which is the focus of this design (see figure 1.1), an endurance of approximately five minutes may be achieved using a battery with an energy density of 400 watt-hours per kilogram. Given that the current state of the art in lithium ion batteries is actually only about 250 Whr/kg, it is clear that electric propulsion is completely unfeasible for any reasonably useful application to which the S-UAV might be put. Thus, by default, a gasoline engine will be used for the design.

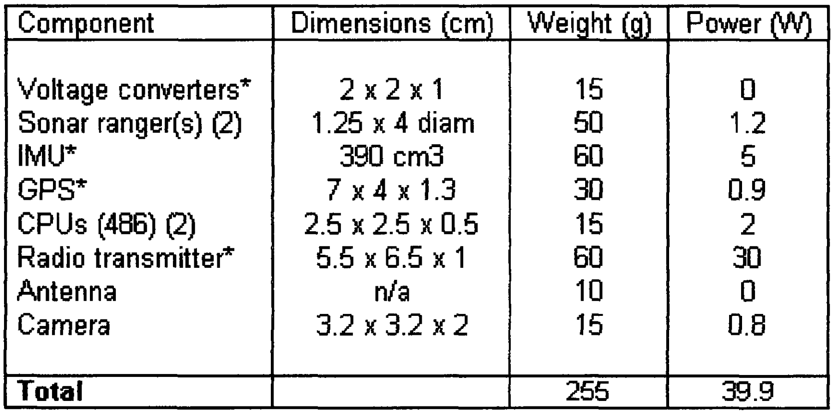
In order to determine a single optimum configuration for the S-UAV, several other decisions were made as well. It was decided that only two rotor blades would be advantageous over three or more blades, as a larger number of blades would increase the weight of the vehicle and would operate at a lower Reynolds number (thus increasing drag and losses). A configuration with multiple fans was considered (such as two fans connected by a wing-like structure), but this would result in a lower thrust-to-power ratio, and would necessitate a very complex mechanical system to synchronize the fans. Also, the concept of a vehicle which could both hover and transition into forward flight (such as a tilt-rotor aircraft) was considered, but this again would result in a very complex system (recall that "simple design" was a high-ranking technical requirement in the QFD) and a high forward flight speed is not a requirement of the vehicle or of any of its potential missions. Thus, the configuration concept downselect process resulted in a simple, single fan, hovering vehicle — a "flying disk" of sorts.

Although a high forward flight speed is not a requirement of the design, the S-UAV must be capable of a certain minimum velocity in order to perform a useful mission in wind. It was estimated that the vehicle requires a "still air" forward speed of 30 km/hr to overcome average wind conditions and maintain the speed of 15 km/hr relative to the ground which is required of the missions (Weiss). To produce forward thrust, the S-UAV can use its control vanes (located below the duct — see figure 4.6) to deflect half of the flow backwards through a slight angle. This way, half of the thrust contributes only to balancing the weight of the vehicle, while the other half contributes to balancing both the weight and the drag forces. Given the size of the S-UAV (see below) and its thrust-to-weight ratio of 1.4 (used in sizing the vehicle), a deflection angle of 12 degrees will result in a forward velocity in excess of 30 km/hr. Alternatively, the vehicle can simply be tilted to produce forward thrust; however, there is a maximum angle to which this can be done without compromising the stability of the vehicle.

4.5 Inboard Profile and Center-of-Gravity Estimate

Before detailed design can begin on the preferred system concept, it is important to get a sense of the eventual locations of the different components within the vehicle, to ensure that there is sufficient space for all required components, and that the vehicle can be suitably balanced. In addition, the center-of-gravity of the vehicle must be made to be in the appropriate location. To this end, a rough inboard profile was done at this stage in the design.

To begin the inboard profile, an estimate of the eventual size of the vehicle must first be made. To do this, a parametric analysis was performed, which is detailed in the thesis of team member Arnaldo M. Leon. The total weight of the vehicle is first determined by solving two equations in two unknowns: an equation for the thrust required to lift a UAV of a certain weight, and an equation for the weight of a UAV capable of supplying a certain amount of thrust. The solution depends on, among other parameters, the weight of the electronic components on board the vehicle. A breakdown of this weight is shown in table 4.3:



Component	Dimensions (cm)	Weight (g)	Power (W)
Voltage converters*	2 x 2 x 1	15	0
Sonar ranger(s) (2)	1.25 x 4 diam	50	1.2
IMU*	390 cm3	60	5
GPS*	7 x 4 x 1.3	30	0.9
CPUs (486) (2)	2.5 x 2.5 x 0.5	15	2
Radio transmitter*	5.5 x 6.5 x 1	60	30
Antenna	n/a	10	0
Camera	3.2 x 3.2 x 2	15	0.8
Total		255	39.9

* estimates

Table 4.3: Preliminary size, weight and power consumption of electronics

Table 4.3 does not include any structural or engine weights, but merely those component weights which will remain constant regardless of the eventual size of the S-UAV. Included also in table

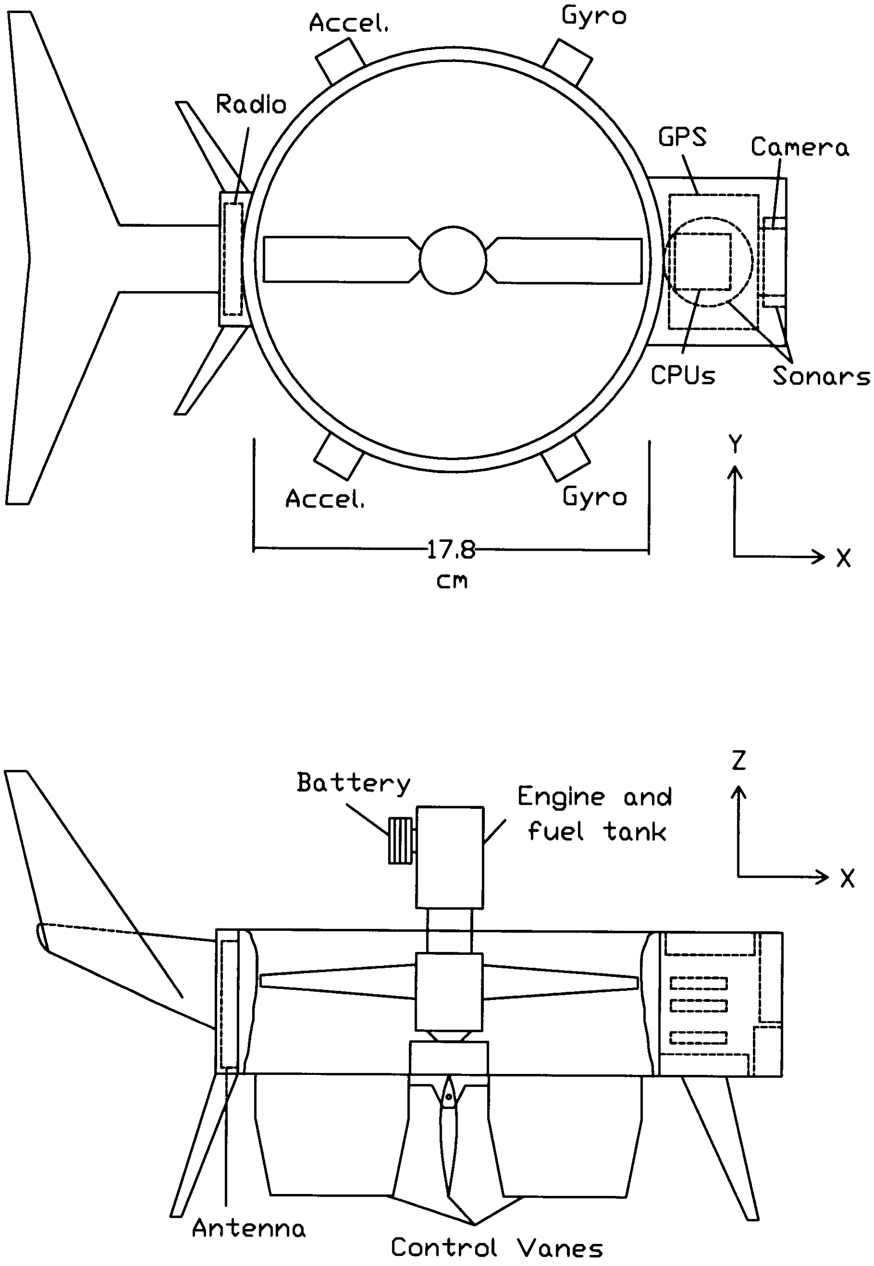
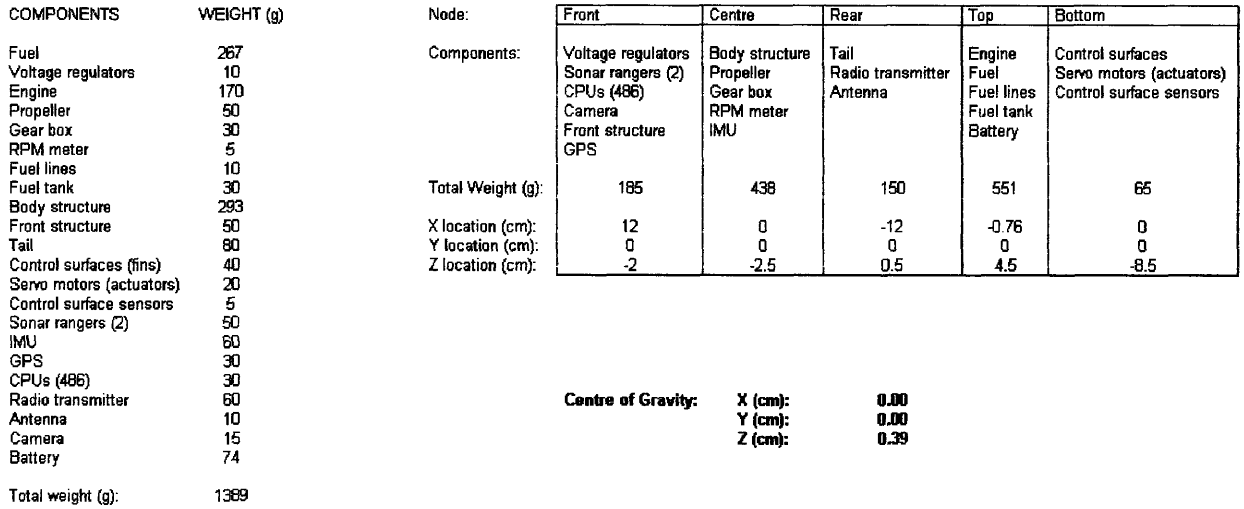


Figure 4.6: Inboard profile for the S-UAV

4.3 is power, which is needed to size the battery which will be required on the vehicle. Once the total vehicle weight has been determined, the duct diameter can be found for a certain total endurance time. For a cruise range of 1 km (at a speed of 15 km/hr, assuming adverse wind conditions) and a loiter time of 15 minutes, the diameter of the duct must be 17.8 cm.

The inboard profile of the S-UAV is shown in figure 4.6. It is a simple design, with a single duct, the majority of the electronics in a structure at the front of the vehicle, the engine and battery above the duct for center-of-gravity purposes (see below) and a tail to provide pitch damping (required due to the equations of motion of the vehicle — see the thesis of Arnaldo M. Leon). As can be seen, there is sufficient volume to house all the electronics; in fact, the size of the housing is somewhat arbitrary, and could be increased slightly if need be. The size of the tail is also fairly arbitrary, and can be adjusted to fine tune the location of the center-of-gravity.

In any airborne vehicle, the location of the center-of-gravity is of great importance to the stability and behavior of the vehicle. From a stability analysis of the S-UAV (see the thesis of team member Arnaldo M. Leon), it was determined that the optimum location for the center-of-gravity is on the axis of rotation of the rotors, and slightly above the top of the duct. Thus, an effort was made to place the components in such a way as to fulfill this requirement. For a preliminary estimate of the center-of-gravity location, the vehicle was subdivided into five areas (front, center, rear, top and bottom) and the weights of all the components in each area were taken to act at a particular node — in effect, the center of gravity for that node. Figure 4.7 shows the weights of every part of the vehicle, the preliminary breakdown amongst the nodes and the estimate of the center-of-gravity.



COMPONENTS	WEIGHT (g)
Fuel	267
Voltage regulators	10
Engine	170
Propeller	50
Gear box	30
RPM meter	5
Fuel lines	10
Fuel tank	30
Body structure	293
Front structure	50
Tail	80
Control surfaces (fins)	40
Servo motors (actuators)	20
Control surface sensors	5
Sonar rangers (2)	50
IMU	60
GPS	30
CPUs (486)	30
Radio transmitter	60
Antenna	10
Camera	15
Battery	74
Total weight (g):	1389

Node:	Front	Centre	Rear	Top	Bottom
Components:	Voltage regulators Sonar rangers (2) CPUs (486) Camera Front structure GPS	Body structure Propeller Gear box RPM meter IMU	Tail Radio transmitter Antenna	Engine Fuel Fuel lines Fuel tank Battery	Control surfaces Servo motors (actuators) Control surface sensors
Total Weight (g):	185	438	150	551	65
X location (cm):	12	0	-12	-0.76	0
Y location (cm):	0	0	0	0	0
Z location (cm):	-2	-2.5	0.5	4.5	-8.5

Centre of Gravity:	**X (cm):**	**0.00**
	Y (cm):	**0.00**
	Z (cm):	**0.39**

Figure 4.7: Preliminary positioning of components and resulting center-of-gravity

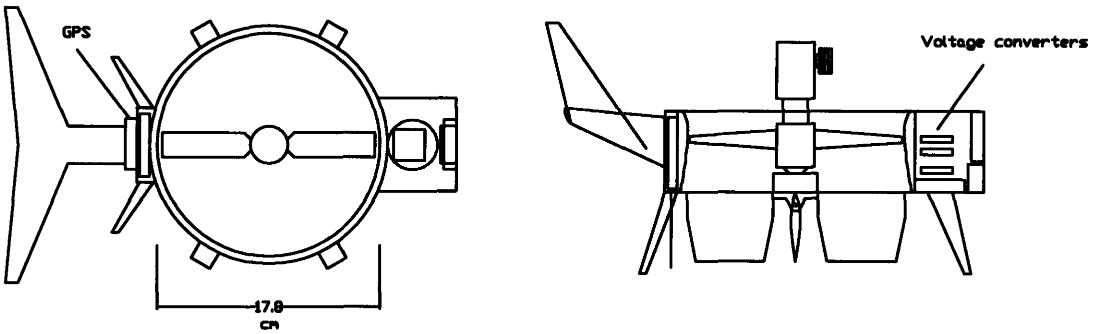
The co-ordinate system used in this analysis has its origin at the center of the top of the duct; X points towards the front of the vehicle, Y points to the side, and Z points up. It should be noted that while the component weights are fairly firm, the locations of the nodes are somewhat arbitrary; they were chosen from within reasonable limits specifically in order to cause the overall center-of-gravity to be in the correct location. It was assumed that within each area there would exist sufficient flexibility in the positioning of the components to allow the placement of the node at the appropriate point. The rear node, in particular, would be quite flexible, as the tail is of unspecified dimensions and could be made higher or longer (within limits, of course) as needed; or, for example, the battery could be specifically chosen to hang off the back of the engine to result in the slight offset (-0.76 cm) of the top node. In any case, it is clear that the desired position of the center-of-gravity is very much achievable, and thus the vehicle can be made to be appropriately stable.

4.6 Interface Weights and Architectural Variants

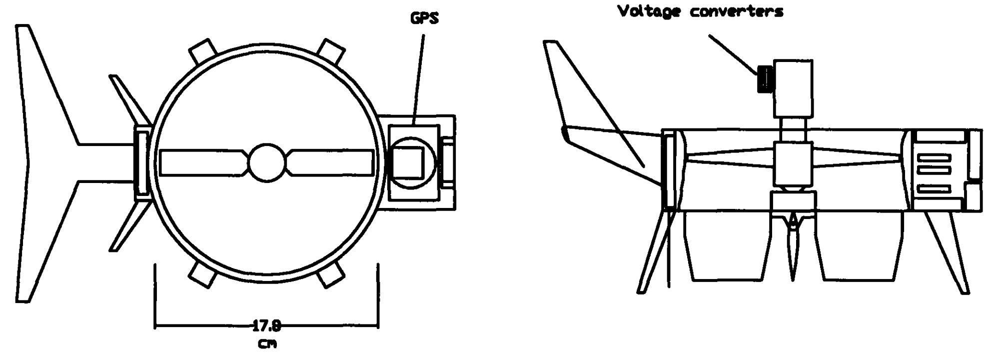
Though it may at first be overlooked, the weight of the interfaces between components and subsystems accounts for a non-negligible fraction of the total weight of any air vehicle. Because interface weight is significant, it is advantageous to attempt to minimize it through the strategic placement of components within the vehicle.

To this end, several variants were generated for the S-UAV with respect to the internal component and interface architecture. The variants, of course, are subject to the constraint that they must allow the center-of-gravity to be in the appropriate location (see above). Figure 4.8 illustrates the differences between these architectural variants, and table 4.4 details the interface weight breakdown of each. Due to the constraints of center-of-gravity and functionality (for example, the camera and collision avoidance sonar must be located at the front), the variants are all fairly similar, though they have important differences. Variant A was the first configuration conceived for the S-UAV; it is similar to the layout detailed in section 4.5 (see figure 4.6), except that the GPS unit is in the rear. All of the voltage converters are in the front. In variant B, the GPS is moved to the front of the vehicle, and the voltage converters are moved to the top, next to the battery. Variant C has the GPS in the front, and the voltage converters are spread throughout the vehicle; each is located in the same area as the component to which it is supplying voltage. This is the architecture illustrated in section 4.5. The weight of a single wire was estimated to be 0.08 grams per centimeter, and this figure was used in the total weight determination. Although the total weight of the interfaces is quite sensitive to this estimate due to the large lengths involved, the relative improvement of the optimum architecture over the others remains constant regardless of the estimate of wire weight.

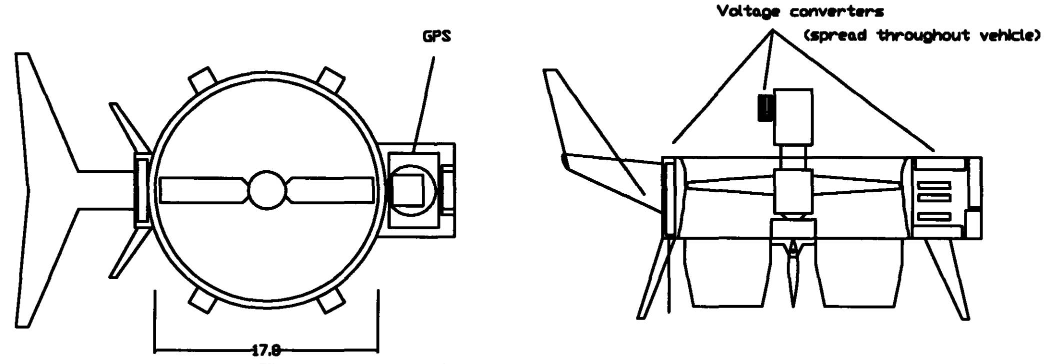
As can be seen, variant C is the optimum component architecture, reducing the total interface weight by about twenty percent. This is mainly due to the fact that the power system enjoys the advantages of both variant A and variant B — a single power line may supply all the components at the front (as in variant A), but power to the radio in the rear does not have to be



Variant A



Variant B



Variant C

Figure 4.8: Schematics of architectural variants

Table 4.4: Interface weights for different S-UAV architectural variants

Interface length densities (g/cm):	single wire	0.08
	twisted pair	0.16
	8-bit serial bus	0.64

					Variant A	**Variant B**	**Variant C**
From	**To**	**Interface Type**	**Interface**	**Length Density (g/cm)**	**Length (cm)**	**Length (cm)**	**Length (cm)**
Sonar	Control processor	signal	twisted pair	0.16	4	4	4
IMU	Control processor	signal	single wire	0.08	60	60	60
GPS Receiver	Control processor	signal	single wire	0.08	35	2	2
Radio	Comm processor	signal	8-bit serial bus	0.64	33	33	33
Radio	Antenna	signal	twisted pair	0.16	1	1	1
Comm processor	Control processor	signal	8-bit serial bus	0.64	0.5	0.5	0.5
Camera	Compression chip	signal	single wire	0.08	1	1	1
Camera	Comm processor	signal	single wire	0.08	3	3	3
Compression chip	Comm processor	signal	single wire	0.08	2	2	2
Position sensors	Control processor	signal	single wire	0.08	40	40	40
Control processor	Actuators	signal	single wire	0.08	40	40	40
Control processor	Throttle	signal	single wire	0.08	15	15	15
RPM meter	Control processor	signal	single wire	0.08	15	15	15
Power supply	Voltage converters	electrical	twisted pair	0.16	15	2	30
Power supply	Ground	electrical	twisted pair	0.16	2	2	2
Voltage converters	Ground	electrical	twisted pair	0.16	1	1	1
Voltage converters	Sonar	electrical	twisted pair	0.16	5	15	5
Voltage converters	IMU	electrical	twisted pair	0.16	50	60	50
Voltage converters	GPS Receiver	electrical	twisted pair	0.16	35	15	2
Voltage converters	Control processor	electrical	twisted pair	0.16	2	15	2
Voltage converters	Comm processor	electrical	twisted pair	0.16	2	15	2
Voltage converters	Radio	electrical	twisted pair	0.16	35	12	2
Voltage converters	Camera	electrical	twisted pair	0.16	4	17	4
Voltage converters	Compression chip	electrical	twisted pair	0.16	2	15	2
Voltage converters	Actuator	electrical	twisted pair	0.16	15	28	15
Voltage converters	Position sensor	electrical	twisted pair	0.16	15	28	15
Voltage converters	Throttle	electrical	twisted pair	0.16	12	2	2
Voltage converters	RPM meter	electrical	twisted pair	0.16	15	5	5
			Total Interface Weight (g):		73	74	59

routed through a voltage converter at the front (as in variant B). It may be noted that the 8-bit interface between the radio transmitter and the communication processor is both heavy and long, and it would seem that moving the radio to the front of the vehicle (and moving a similarly-weighted set of components — such as perhaps the GPS and the sonar altimeter — to the rear for balance) would improve the total weight a great deal. This is true, but it was felt that due to the high output power required to communicate from behind an obstruction (see section 5.1, below), the danger of electromagnetic interference from the radio affecting the other systems would be much greater if the transmitter were placed in such proximity to the other components. This is an example of a systems integration issue, and will be dealt with further in section 5.7.

From the above analysis, it is also clear that the interfaces do indeed make up a significant fraction of the total weight of the vehicle, and that minimizing their weight is truly a worthwhile effort.

4.7 Preliminary Cost Estimate

Due to the unprecedented size of the S-UAV and the necessity of customizing some of the components (such as the radio and the IMU), it is difficult to arrive at a precise figure for the total cost of the vehicle. However, it is important to make an estimate in order to satisfy oneself that it would be feasible for civilian markets (particularly since cost was emphasized to such an extent in the market assessment — see section 2), and to determine whether there are any cost drivers in the design which may require attention.

Table 4.5 shows a preliminary breakdown of the cost associated with the electronic components for the S-UAV:

Component	Cost
Voltage converters*	$100
Sonar rangers (2)	$100
IMU*	$3,000
GPS*	$1,000
CPUs (486) (2)	$70
Radio transmitter	$500
Antenna	$50
Camera	$250
Total	$5,070

* estimates

Table 4.5: Cost breakdown for electronic components

Cost estimates were based on research into the prices of components with similar characteristics to those required for the S-UAV. From this table, it is clear that the IMU is a cost driver; effort should be put into designing a custom IMU which has a cost more consistent with the other components. This would result in a significant decrease in the total price of the vehicle.

Judging from table 4.5, it is estimated that once in production the entire S-UAV could be constructed for approximately $10,000, when the structure, engine and manufacturing of the vehicle are taken into account. Other costs of ownership, such as operations and maintenance costs or the cost of the ground station, are not included, but should keep the total life-cycle cost in the neighborhood of twenty or thirty thousand dollars (as a rough estimate). This total price tag should be within the budgets of most organizations for which the vehicle is intended.

Section 5: System Design

This section deals with the more detailed level of design which follows the conceptual design. Because the design of the S-UAV was a team effort, responsibility for the detailed design of the subsystems was divided up amongst the team members. Thus, this section will enter into detail only for those subsystems which were within the domain of the author's responsibility: the communication system, the imaging system, and to a lesser extent the power system. The remaining subsystems will be dealt with briefly, and reference will be made to the team member's thesis in which a more thorough treatment may be found.

5.1 Communication System

The task of the communication system is to receive commands from the ground station and pass them on to the appropriate subsystem, and to send data from the other subsystems to the ground. In order to function reliably during the missions for which the S-UAV is being designed, the communication system must fulfill several important requirements. First and perhaps foremost, it must have a range in excess of two kilometers. It must possess the ability to communicate with the ground station even when behind an obstruction of some kind, such as a downtown building, and not within line-of-sight of the ground station. In addition, it should have a sufficient data throughput capacity to allow transmission of video images to the ground station. Finally, it should be lightweight, and consume as little power as possible.

The system is composed of three components, and is shown in schematic block diagram form in figure 5.1. The processor is a 486, weighing 15 grams and drawing 0.1 watts of power. It is responsible for processing the commands received from the ground station and sending them to either the control system or the imaging system, and for collecting the data to be transmitted to the ground. The antenna is a simple half-wavelength omnidirectional wire antenna; it is 6.2 cm long, and weighs approximately 10 grams (with interface).

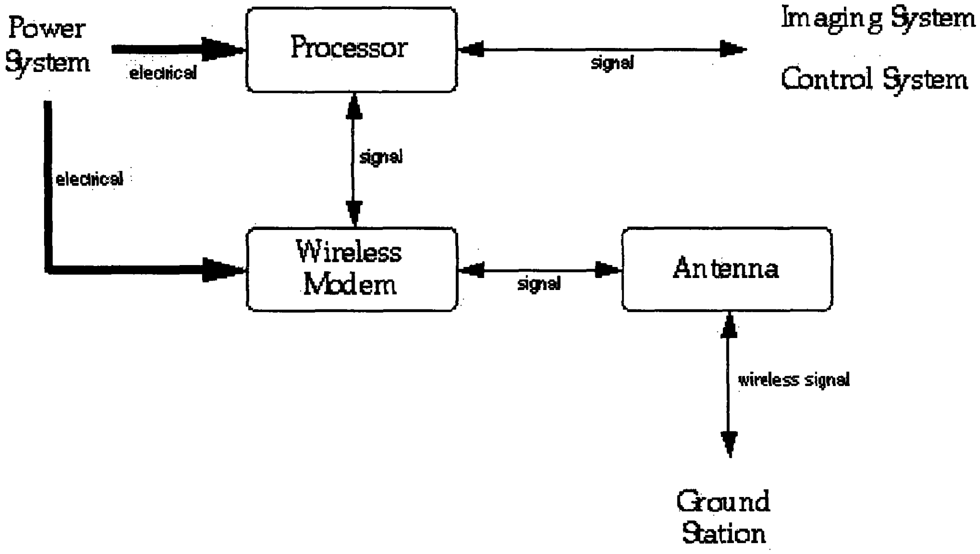


Figure 5.1: Schematic block diagram for the communication system

The transmitter itself is modelled on the RangeLAN2 6301 Serial OEM Module wireless modem manufactured by Proxim. It was chosen primarily for its weight (less than 60 grams), and for its high data throughput rate of 1.6 million bits per second. Although the RangeLAN2 is small, measuring 5.6 cm by 9.4 cm, the custom-made modem used on the S-UAV would need to be slightly smaller (see section 4.5).

For transmission, the modem makes use of spread-spectrum technology — specifically, it is a frequency-hopping spread-spectrum system. Systems of this kind hop from frequency to frequency (within a specified band) in a pseudorandom sequence, which is known by both the transmitter and the receiver prior to transmission. Several advantages are gained by this. First of all, communication between the S-UAV and the ground station will be less susceptible to interference, as a specific frequency is used for only a small fraction of the communication time. For a vehicle in a military scenario, spread-spectrum communication is invaluable, as the transmission is impossible to intercept and/or jam without prior knowledge of the frequency hopping sequence and the dwell time at each frequency. Through the use of cross-correlation between the incoming signal and the known pseudorandom pattern, the useful signal can be very effectively distinguished from background noise, resulting in a drastic reduction in the wave power required to reach the receiver. Also, the effects of multipath interference (a reflected signal and a direct signal interfering destructively at the receiver), which can be lessened by the use of a directional ground antenna, is further mitigated by the use of frequency-hopping (Wong, p. 142). The modem to be used on the S-UAV operates at frequencies between 2.4 GHz and 2.4835 GHz; in the United States, this frequency band is designated as one of the industrial, scientific and medical (ISM) bands, and hence is available for use without a license.

In order that the S-UAV be able to perform all the missions envisioned for it, the communication system must be able to function at a range of more than two kilometers. On a line-of-sight, the power attenuation of electromagnetic waves in free space is given by

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2 \qquad (5\text{-}1)$$

where P_r and P_t are the received and transmitted powers, G_t and G_r are the gains of the transmitting and receiving antennas, λ is the wavelength and d is the transmitter-receiver distance [Boithias 26]. The gain of an isotropic antenna is unity. To find the minimum power which needs to arrive at the receiver, the receiving characteristics of the RangeLAN2 were chosen as a model. The RangeLAN2 has an output power of 0.1 W at a wavelength of 12.5 cm (2.4 GHz), and a maximum range of 300 m using two isotropic antennas. Substituting these values into equation 5-1 yields a minimum receiving power $P_{r,\,min}$ of 1.1×10^{-10} watts. This seemingly minuscule power requirement is possible due to the signal-to-noise enhancement capabilities of spread-spectrum technology mentioned above. To increase the range from 300 m, it was assumed that the transmitted power from the modem has a roughly linear dependence on the power which is supplied to it.[†] Also, a directional antenna was considered for the ground station. For a parabolic reflector, the gain is given by

$$G = 5\left(\frac{D}{\lambda}\right)^2 \qquad (5\text{-}2)$$

where D is the diameter of the antenna. So, with an isotropic antenna on the vehicle and using the given $P_{r,\,min}$, equation 5-1 gives simple relationships between required power and range for different ground antenna diameters:

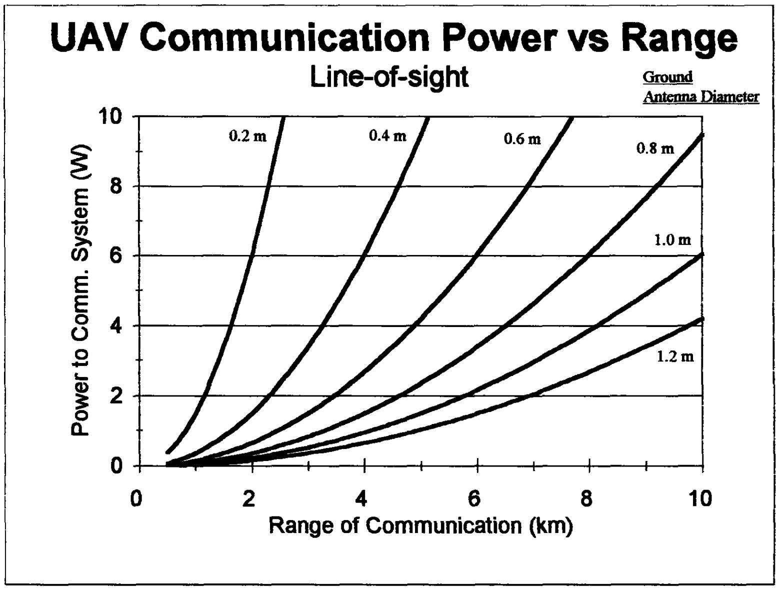


Figure 5.2: Unobstructed communication range

As can be seen, including a directional antenna with the ground station increases the range of communication considerably. For this reason, it was decided to use a 1 meter antenna as part of the ground station; using an antenna of this size with the existing RangeLAN2 (input power of

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[†] This is not to say that an existing modem, such as the RangeLAN2, can be made to transmit more power simply by "turning up" the input power; rather, it was assumed that if a similar device were to be constructed, designed to have a larger output power, this device would require a linear increase in input power.

1.75 watts) increases the range from 300 m to over five kilometers. Although this is far more than would be required during the S-UAV's mission, it must be noted that these figures apply only to situations when the vehicle is within line-of-sight of the ground station — when this is not the case, range will be at a premium.

The assumption of linearity between input power and output power used in the above model was confirmed by a brief study of existing wireless modems. Several modems made by Motorola and Xetron were surveyed to determine the trend of input power with increasing output power. These particular modems were chosen because they are all frequency-hopping spread-spectrum systems, and all have identical data throughput capacities (19.2 kbps). The results of the study are shown in figure 5.3:

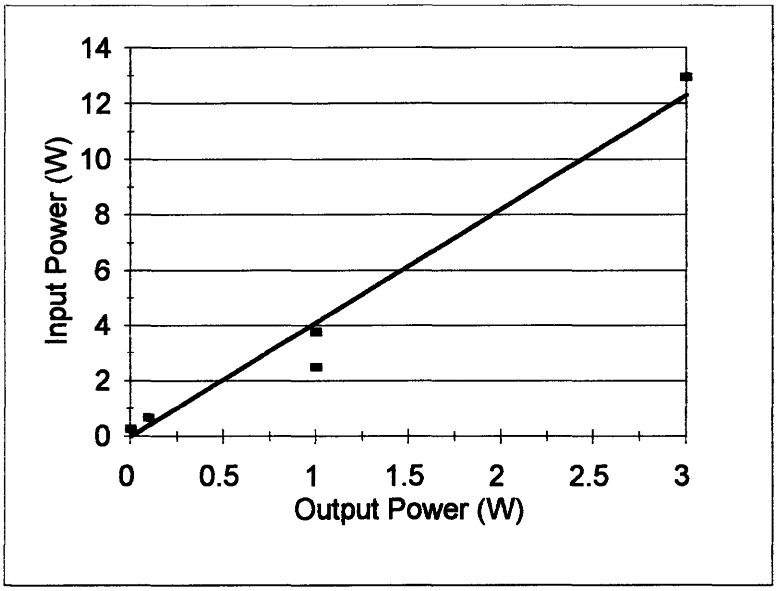

Figure 5.3: Input-output relationship approximation for wireless modems

It is important to note that Proxim modems were not included for two reasons: they have a higher data throughput than those modem considered, which might skew the results, and they all have an output power of 0.1 W. The modems used in the above study displayed variety in terms of power requirements and consistency in terms of other characteristics; from the results, it can be seen that a linear assumption for the relationship between output power and input power can be a reasonable approximation for a top-level design such as this.

The largest challenge facing the design of the S-UAV communication system is providing the vehicle with the capability of communicating with the ground station from behind a solid obstacle. In a general sense, there are several ways to deal with the non-line-of-sight problem, not all of which are feasible for a small UAV such as the one being designed. An overhead relay could be deployed, so that although there may not exist a line-of-sight between the vehicle and the ground station, each would be able to "see" the relay. However, it was envisioned that the S-UAV would be a stand-alone vehicle (from an "ease of use" perspective), which could be prepared and launched quickly, and operate on its own. For missions which would require fast response and deployment times (such as law enforcement or news coverage), the launching of a balloon or a second UAV to serve as a communication relay would be impractical. As an extreme extension of the overhead relay concept, satellite communication is a possibility. This too is impractical due to the vast distances between the vehicle and a satellite. By equation 5-1, power attenuation goes as the square of the distance, resulting in enormous power losses when transmitting to a satellite. To compensate for this, the vehicle would require either a very large power supply or a high-gain directional antenna, neither of which is feasible for reasons of weight.

The sole remaining option, then, is to make use of radio waves' tendency to scatter around the edges of objects. This can be accomplished best by waves of low frequency and therefore long wavelength (AM and FM radio signals can be received anywhere because they have wavelengths in excess of a few meters). However, the data rate which is required for the S-UAV to transmit images cannot be carried on waves of low frequency. So, enough power must be transmitted from the modem to ensure that even waves at 2.4 GHz are somewhat scattered by an obstacle. If the obstruction is modeled as a knife edge of height h with respect to the direct path from the S-UAV to the ground station, as shown in figure 5.4, the power which arrives at the receiver may be calculated.

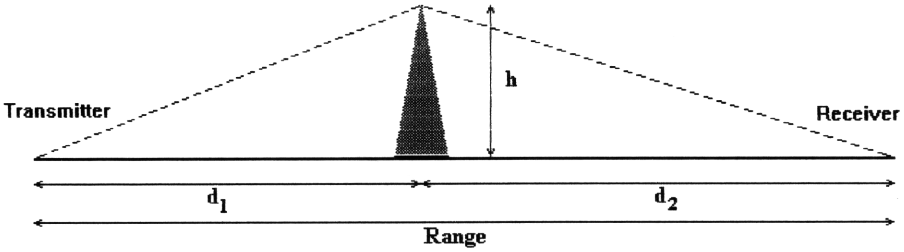

Figure 5.4: Obstruction model

With *v* as the variable

$$v = h\sqrt{\frac{2}{\lambda}\left(\frac{1}{d_1}+\frac{1}{d_2}\right)} \tag{5-3}$$

There is an empirically determined relationship between *v* and the power loss P/P_0 to which Boithias (p. 194) gives an approximation (valid for $v > -0.7$):

$$10\log\frac{P}{P_0} = -6.9 + 20\log[\sqrt{(v-0.1)^2+1} - v + 0.1] \tag{5-4}$$

In this expression, P_0 is the power which would be received without an obstruction present. So, if we assume that the ground station has a directional antenna with diameter 1 m, and the obstruction is taken to be roughly halfway between the S-UAV and the ground station, the power required for a given range can be calculated:

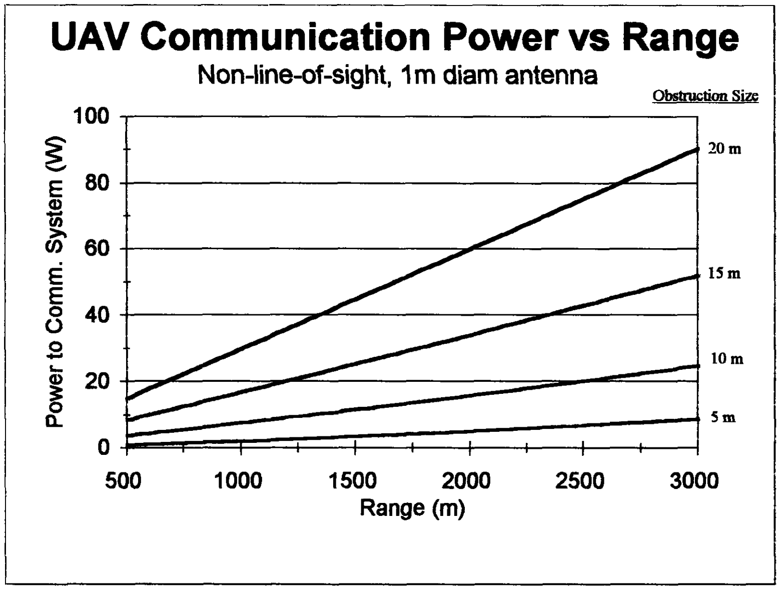

Figure 5.5: Communication power required from behind obstructions

From this plot, it is clear that it is difficult to communicate when the vehicle is not on a line-of-sight with the ground station. Fortunately, for most of the missions envisioned for the S-UAV, long range and obstructed communication are not required simultaneously. The military mission requires a range of over 2 km, but involves only line-of-sight communication. Law enforcement and news coverage require the ability to function from behind a 40 m wide building (which would correspond to a 20 m obstruction by the above model), but the total range need not exceed a kilometer. The exception is the search and rescue mission, which would require communication from behind a significant obstruction (perhaps as large as a mountain) at a range of several kilometers. This particular mission might be deemed too much of a strain on design requirements, and may be dropped from consideration. Thus, an input power of about 30 W would be needed to cover the communication requirements for the majority of the S-UAV missions.

Of course, when designing a component that consumes 30 watts of power, consideration must be given to potential overheating. Since the radiated output power of the transmitter is roughly 1.7 watts, this leaves over 28 watts of power which must be dissipated as heat. Assuming similar specifications to the RangeLAN2, the radio has an upper temperature limit of 60 °C, beyond which it will not operate and/or will suffer damage. Clearly, the dissipation of 28 W of power must not cause the equilibrium temperature of the radio to exceed 60 °C; some kind of heat sink must be found. Fortunately, the use of the duct itself as a heat sink maintains the temperature of the radio at a reasonable temperature. The duct makes an excellent heat sink, primarily due to the fact that air is being forced through it at high velocity in order to keep the S-UAV aloft. A heat transfer analysis was performed (detailed in the appendix) which found that for an aluminum duct of thickness 1.5 cm and height 6.5 cm, and an air flow with velocity 24 m/s (Leon) and temperature 20 °C, the equilibrium temperature which the wireless modem will reach is 35.5 °C — well below the maximum operating temperature. This temperature is weakly dependent on the duct thickness and height, but more strongly dependent on the material's thermal conductivity. If a carbon composite is used for the duct (for a slight weight savings and strength increase, but also a cost increase), the temperature of the radio has the potential to exceed the maximum operating level. The thermal conductivity of a carbon composite may be 20 W/mK or less, as opposed to aluminum's 230 W/mK, which would increase the radio's temperature to 63 °C or more.

One design alternative which would reduce the power required to communicate from behind an obstruction is to increase the frequency of transmission to the highest unlicensed ISM band, 5.8 GHz. Although P/P_0 decreases as roughly the square root of the frequency, the gain of a given diameter antenna increases by the square of the frequency; thus at 5.8 GHz, the input power required for a 20 m obstruction and a range of 1 km has decreased to about 12 W. However, one trade-off is the beamwidth of the ground antenna — this quantity decreases with increasing frequency, and can easily reach a point where pointing accuracy becomes an issue (see section 5.8).

The problem of non-line-of-sight communications is greatest for urban scenarios (i.e. law enforcement and news coverage), where obstructions are not easily avoided, and range can reach a kilometer. In these situations, an alternative to using a high-power transmitter or deploying an overhead relay might be to use an existing communication relay on the roof of a tall building. This would require prior agreement with the operator of the relay and possibly with the FCC, but it could serve as a viable, reliable, and easily implemented method of ensuring line-of-sight communications within an urban environment.

5.2 Imaging System

The imaging system is the centerpiece in the performance of any of the missions envisioned for the S-UAV.[†] Indeed, the sole reason for the existence of the rest of the vehicle is to carry the imaging system to a location at which there is something to image, and then carry it back. Thus, it is important that this system be able to accomplish all that is required of it, or there will be little point in performing the mission at all. It must be able to provide images at a sufficient rate to at least closely approximate video, in order to allow navigation and maneuvering by the pictures received at the ground station; for this same reason, it must provide these images in real time. However, the data output rate of the system cannot exceed the throughput capacity of the communication system. If the vehicle is to fulfill all the point performance requirements detailed in section 4.1, the imaging system should have the ability to orient in any of a downward, forward or upward direction, though this orientation need not change during flight. Finally, the shutter speed of the camera must be fast enough to avoid blurry pictures, due either to the vehicle's forward velocity or to vibration, and at the same time slow enough to ensure adequate exposure.

The imaging system for the S-UAV is composed of two components, as shown in figure 5.6. The camera is a high resolution micro CCD board level camera, manufactured by Edmund

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[†] In the case of the environmental studies mission, the imaging system (essentially the payload for the other missions) would be replaced with appropriate instrumentation payload; this will be discussed later.

Scientific Company. It has a resolution of 570 x 350 pixels, a 3.7 mm f/5 lens with a field of view of 60 x 45 degrees, and a data output of 8 bits per pixel. It is 3.2 cm square by 2.0 cm deep, weighs 14.5 grams, and sells for $247 US. The compression chip is a 21230 Video Codec chip, manufactured by Digital Semiconductor. It is capable of the real-time compression of images into JPEG format at a rate of up to 30 frames per second.

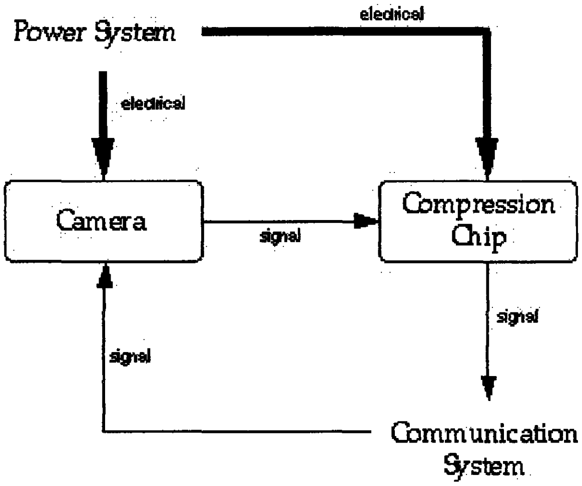


Figure 5.6: Schematic block diagram for the imaging system

It is desired that the output of the imaging system approximate full-motion video as closely as possible. The extent to which it is capable of this is determined by the rate at which it can output frames without exceeding the data throughput capacity of the communication system. The maximum frame rate at which the camera can be operated is 30 frames per second (fps), which is also the most that the compression chip can handle; this then is an absolute upper limit, regardless of the communication system's capabilities. At a resolution of 570 x 350 pixels at 8 bits per pixel, each image has an uncompressed size of 1.596 million bits. So, without a compression chip the imaging system could produce only a single frame per second and would still consume virtually all of the communication system's capacity (of 1.6 million bits per second). Clearly, some kind of compression is required. The JPEG (Joint Photographic Experts

Group) format is a widely-used algorithm for image compression which can reduce the data size of the image considerably. Although the precise compression ratio achieved with JPEG varies substantially with the characteristics of the image itself, Bhaskaran (p. 3) indicates that, as an example, a video conference of 15 fps having an uncompressed data stream of 30.41 Mbps can be compressed to anywhere between 64 kbps and 768 kbps. At 15 fps, the S-UAV's camera produces 1.596 x 15 = 23.9 Mbps; thus, if Bhaskaran's model is taken as a guide, an output of between 50 kbps and 600 kbps can be predicted for the imaging system. This is well below the capacity of the wireless modem, leaving more than sufficient room for the transmission of other important data. Although it would be necessary to test to determine the actual compression ratios achieved, this model predicts that the frame rate could even be increased to the maximum allowable 30 fps, and consume a maximum of 1.2 Mbps of the modem's capacity. Thus, it is clear that with data compression technology, the S-UAV's imaging system can do an excellent job of approximating full-motion video, which is invaluable for such applications as news or sports coverage.

It is important that the camera be able to "look" in a variety of directions in order to be useful for a variety of missions. For military or search and rescue missions it would need to point directly down, for law enforcement or news gathering it would likely point somewhat obliquely down and forward, for the inspection of a building it would point directly forward, and for the inspection of a bridge it would be required to point directly up. This flexibility, in particular the capability to orient upwards, is difficult to provide without exposing the camera to the elements. One way to solve this problem is by means of an adjustable mirror, which would allow the camera to remain fixed (oriented forward) and could be tilted in such a way as to reflect images from below or from above. The mirror could be removed for building inspection or whenever it was desired that the camera point forward. Adjustment of the mirror could be manual (i.e. it could be set before take-off, and remain in the same position throughout the mission), which would minimize the complexity of the system, or it could be made to be automatic by means of a small actuator which could be run by the communication processor.

This would require the inclusion of the actuator in the payload sizing considerations which were discussed in section 4. A sizeable challenge involved with the construction of the mirror system would be to ensure that it was fastened securely enough to the vehicle that vibration is kept to a minimum, or at least that the vibration of the mirror is in sync with that of the vehicle as a whole; it would be difficult but essential to prevent the mirror from vibrating and causing the images to jump around significantly.

The shutter speed of the camera is an important factor in determining the quality of the images obtained by this system. First of all, it must be fast enough to avoid blur, which may arise from two sources: vibration of the vehicle and forward velocity. The engine proposed for use in the S-UAV has a speed between about 10,000 and 17,000 RPM, or between about 150 and 300 Hz. At these frequencies, it is unlikely that the amplitude of vibration will be very large (Weiss), unless resonance is encountered (which is difficult to predict theoretically). However, it must be ensured that the engine does not set up resonance with the shutter itself, which could result in damage to the camera; thus, the shutter speed should be set well outside this engine frequency range. A speed of $^1/_{400}$ second should ensure that resonance with the engine is avoided. Blur can also arise from the forward motion of the vehicle itself. Graham (p. 94) gives an expression for the image blur b as

$$b = \frac{fVt}{H} \tag{5-5}$$

where f is the focal length of the camera, V and H are the speed and altitude of the aircraft respectively, and t is the exposure time. If we consider a law enforcement mission where the S-UAV is travelling at its top speed of 30 km/h and at an altitude of only 10 m, a $^1/_{400}$ second shutter speed gives (for the 3.7 mm lens) an image blur of less than 8 μm. In reality, the vehicle's typical speed will be only 15 km/hr for most missions; its top speed is intended only as a means of overcoming wind conditions. The sensor active area of the camera is 3.6 mm in the vertical direction and is divided into 350 pixels, so each pixel is more than 10 μm in size.

Therefore, at the shutter speed considered, the image blur does not exceed the pixel size, and so the image should not appear blurry.

At this shutter speed, it is reasonable to question whether enough light will be admitted to the camera to cause a reasonably bright image. The sensitivity of the camera is quoted as being 0.5 lux, a lux being a measure of light intensity per unit area. It was assumed that this minimum illuminance is at the slowest possible camera shutter speed of $^1/_{60}$ second; so, it would be reasonable to assume that a useful image is created by a minimum of 0.5 x $^1/_{60}$ = 0.0083 lux seconds. At the shutter speed considered, then, the camera would require 3.3 lux to form an image. For an overcast day, the illuminance of daylight is (Graham pp. 82-83)

$$E_{d(overcast)} = 0.26E_{su} + 0.54E_{sk} \tag{5-6}$$

where E_{su} and E_{sk} are contributions from sunlight and skylight, respectively, which are expressed in lux and given in terms of the solar altitude θ_s:

$$E_{su} = (142032\sin\theta_s)\ 10^{-\frac{0.1}{\sin\theta_s}} \tag{5-7}$$

$$E_{sk} = 18830\sqrt{\sin\theta_s} \tag{5-8}$$

The amount of light which is reflected off a surface is known as the reflectance, and values for urban areas range from about 2 percent for fresh black asphalt to about 30 percent for concrete (Graham p. 81). So, for an overcast day with the sun low (20 degrees) in the sky, even if we assume the S-UAV is in shadow and neglect the E_{su} sunlight term, fresh black asphalt will still deliver over 100 lux to the camera — more than enough for reasonable exposure.

The field of view of the camera is 45 degrees in the vertical direction and 60 degrees horizontally. At an altitude of 10 meters, this corresponds to an area of 8.3 m by 11.5 m which can been seen by the camera; this should suffice for most law enforcement or news coverage applications (and if a larger area is desired, the S-UAV can simply be operated at a higher altitude). At an altitude of 100 m, the area is increased by a factor of ten on each side. This can be used to determine the force of the turns which the vehicle must make when imaging an area in a military scenario, assuming that a back-and-forth pattern is employed. Since the image area is 115 m wide, the S-UAV must make a turn with a radius of at most $^{115}/_{2} = 57$ m in order to ensure that all the ground is covered. At the vehicle's typical forward speed of 15 km/hr, this results in a turn of only 0.03 g. Even with an allowance for a sharper turn in order to allow for some overlap, the force of the turns required is not significant.

The angular resolution of the camera (field of view over number of pixels) is 2.2 milliradians in the vertical direction, and 1.8 milliradians in the horizontal direction. Thus, at an altitude of 100 m, the camera can discern detail down to about 20 cm, which should be useful for military surveillance. At the other extreme, infrastructure inspection would be performed at distances of a meter or so, which would result in a resolution of about 2 mm. This would be sufficient to identify erosion, rust deposits, major cracking, or other signs of structural damage.

For a mission which required a payload other than an imaging sensor, such as the environmental studies scenario described in section 2, the imaging system would be replaced by an appropriate alternative instrument. The remainder of the vehicle would not require any modifications, provided the new instrument was of roughly the same size and weight; certainly no architectural changes would be required. The compression chip would likely be removed as well as the camera, since the vast majority of scientific instruments output data at a much slower rate than an imaging sensor. The new sensor would simply provide data to the communication processor, which would send it to the ground just as it does with images. In terms of configuration, the payload of the S-UAV is completely modular, which fulfills an important requirement to arise from the QFD analysis of section 3.

5.3 Power System

The power system, as the name implies, is responsible for supplying electrical power to all the components in the S-UAV. This is done by means of a battery and a set of voltage converters, as shown in figure 5.7. Voltage converters are necessary because the electronic components on the vehicle operate at several different voltages, and hence cannot be powered directly from the same battery.

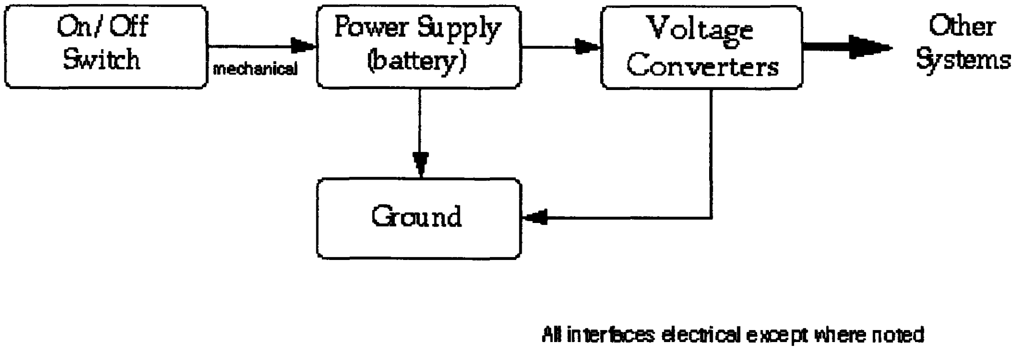
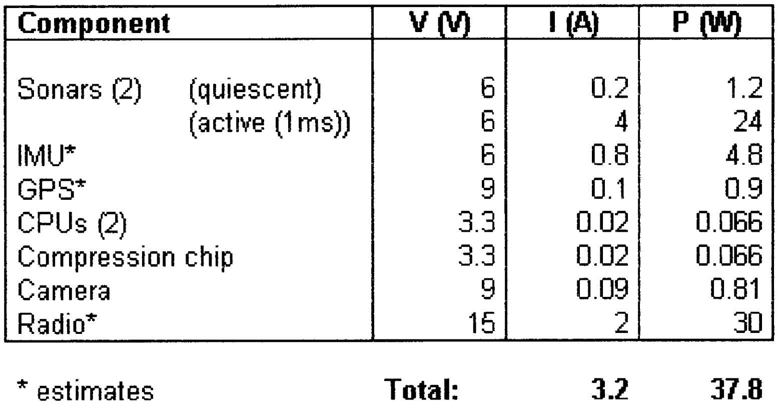


Figure 5.7: Schematic block diagram for the power system

In the above figure, “ground” refers to electrical ground, rather than the ground station. The battery is a lithium ion battery, with an energy density of 250 Watt-hours per kilogram. In order to provide power to all the systems for the entire endurance of the vehicle, the battery must weigh about 75 grams.

The voltage and current requirements of the various electronic components are outlined in table 5.1:



Component	**V (V)**	**I (A)**	**P (W)**
Sonars (2) (quiescent)	6	0.2	1.2
(active (1ms))	6	4	24
IMU*	6	0.8	4.8
GPS*	9	0.1	0.9
CPUs (2)	3.3	0.02	0.066
Compression chip	3.3	0.02	0.066
Camera	9	0.09	0.81
Radio*	15	2	30
* estimates	**Total:**	**3.2**	**37.8**

Table 5.1: Component power requirements

Note that the current and power totals in table 5.1 do not include the active sonar values, as these levels are achieved only for millisecond pulses, once or twice every second. To minimize the number of voltage converters required, it is desirable that as many components operate at the same voltage level as possible. For example, the CPUs and the compression chip may all be run off of a single voltage converter. However, the sonar modules require a linear regulator due to their need for short pulses of large current (DeBitetto et. al.), so no other components may be run on a circuit with them. Table 5.1 does not consider the several small instruments on board the vehicle which also require electrical power, such as the RPM meter, the actuators or the control surface sensors. These would likely need to be custom made, so information regarding power requirements is difficult to obtain at this stage. However, the power consumption of these instruments will in all probability be small, especially in comparison to the consumption of the radio transmitter. Instruments such as these are typically run on about 5 volts, and draw on the order of 100 milliamps (for a power consumption of half a watt). Ideally, all three of these will require the same input voltage, since they are all located in the lower part of the vehicle and would thus require only a single voltage converter.

Lithium ion batteries are available in a wide variety of sizes and voltages; for the S-UAV, one must be custom made to weigh 74 grams. Voltage converters are available from Power Trends which are capable of stepping up from the battery voltage or stepping down, thus making all required input voltages available. These converters are listed as weighing 7.5 grams each, but this includes a good deal of excess packaging, and could be significantly reduced in weight either by custom ordering or by simply altering existing units.

5.4 State and Terrain Estimation System

Perhaps the largest difference between the S-UAV and a model helicopter is the degree to which the S-UAV is aware of its motion and surroundings. This level of autonomy is the responsibility of the state and terrain estimation system, in conjunction with the control system. The estimation system must determine the vehicle's position relative to the ground station, its velocity and acceleration, and it must sense obstacles so that the control system may avoid them. A collision avoidance system was the top-ranking technical requirement to emerge from the requirements analysis (see section 3); thus, this is a critical feature to include on the vehicle. The average forward speed of the S-UAV is about 15 kilometers per hour, so obstacles must be sensed sufficiently far away that a collision may be averted. In addition, as is the case for all the systems, the estimation system should be lightweight and compact.

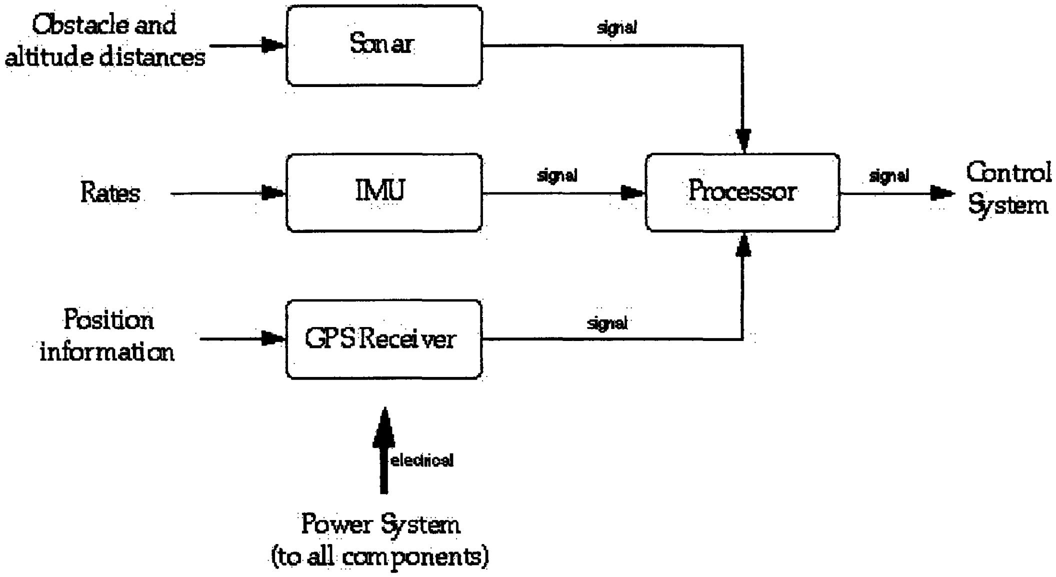


Figure 5.8: Schematic block diagram for the estimation system

The schematic block diagram for the estimation system is shown in figure 5.8. It is composed of a 486 processor (of the same type used for the communication system) and three types of sensor: sonar for detecting obstacles and determining altitude, an inertial measurement unit (IMU) for determining velocity and acceleration, and a global positioning system (GPS) receiver for detecting the vehicle's position relative to the ground station and for avoiding drift in the IMU. Data from all three sensors are fed into the processor, which then instructs the control system as to the state of the vehicle and the potential for collision.

On board the S-UAV, there are two sonar units — one for measuring altitude, and one for detecting obstacles in the forward flight path of the vehicle. Both units are composed of a Polaroid 600 Series Instrument Grade Electrostatic Transducer and a Polaroid 6500 Series Sonar Ranging Module. Each transducer is 4.3 cm in diameter and 1.17 cm thick, and weighs 8.2 grams; each module is 5.7 cm by 4.5 cm by 1.5 cm, and weighs 18.4 grams. The module requires a driving voltage of 6 volts DC, and draws 0.1 amps of current while quiescent and 2.0 amps during each output pulse of one millisecond. A package of two transducers and two modules is available from Polaroid at a price of $99 US.

The operation of the sonar module is shown in figure 5.9. While power is supplied to the module (i.e. V_{CC} is high), a ping is triggered in the transducer by bringing the INIT input high. The receiver is inhibited by an internal blanking signal for 2.38 milliseconds in order to prevent the ringing of the transducer from being detected as a return signal. This blanking effectively restricts the sonar from detecting objects closer than 40 centimeters, although the blanking time can be decreased provided the transducer is sufficiently damped. The ECHO signal output is then brought high when the return signal is detected.

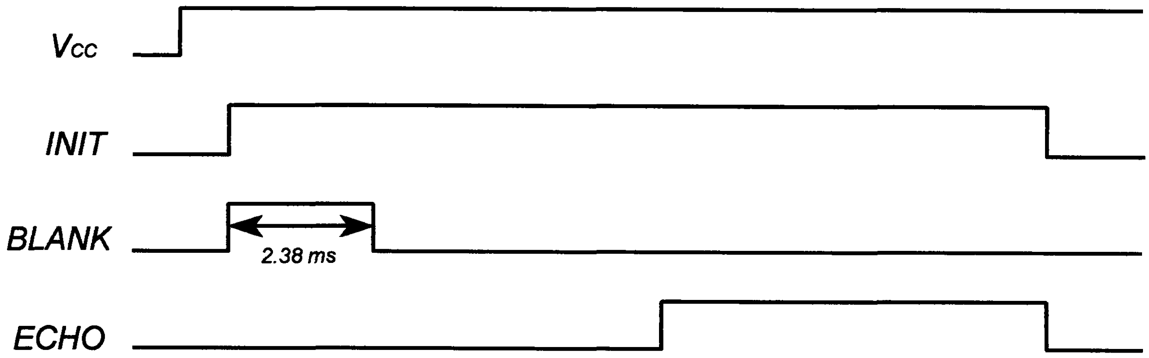


Figure 5.9: Sonar module operation cycle

In the missions for which the S-UAV is intended, it is not foreseen that the blanking time on the sonar ranger will be problematic. The scenarios do not require the vehicle to approach within 40 cm of any object, and it is assumed that the S-UAV will not be required to land autonomously (i.e. when it is within 40 cm of the ground, a human operator will be nearby to guide and control it).

Beginning when a signal is emitted by the transducer, the receiver amplifier gain is increased incrementally at discrete times, since an echo which takes longer to return will be weaker and hence will require more amplification. This gain reaches a maximum at 38 milliseconds; thus, according to the technical specifications, "sufficient gain may not be available for objects greater than 35 ft away." However, by replacing a resistor indicated in the specifications, the maximum gain may be increased by up to a factor of four (beyond this, module operation becomes unreliable). By increasing this gain, the range of the sonar can be increased to 70 feet (since wave attenuation goes as the square of the distance travelled). At its maximum forward speed of 30 km/hr, the S-UAV travels 70 feet in about 2.5 seconds — again, the mission requirements will very rarely call for the vehicle to actually attain this velocity relative to the ground. Time must be allowed for the detection of an obstacle, the processing of received data, a command to be sent to the actuators, and the control surfaces to be deflected — this time is estimated at between ¼ and ½ second (Paduano). In addition, time must be allowed for the vehicle to make a turn to avoid a collision. An estimate of this time, based on the vehicle's forward speed of 30 km/hr, is about one and a half seconds (the control response characteristics of the S-UAV will be detailed in the thesis of team member Young-Rae Kim). Thus, by acquiring a range measurement at least twice every second, the vehicle can ensure that any potential obstacles in its flight path are detected and avoided.

Sonar was selected as the range-finding method because of its low cost, and because it was not foreseen that great range and accuracy would be required of the measurements. However, it must be realized that this poses certain limitations on the estimation system, particularly with respect to altimetry. Since the speed of sound varies with temperature, accurate sonar measurements would require calibration before every flight; in addition, the accuracy of sonar suffers in rain. Perhaps the greatest limitation lies with the range attainable by the sonar module. By increasing the gain of the receiver amplifier by a factor of four, the range of the sonar can be increased to 70 feet, or 21 meters. This is not sufficient to allow constant altimetry readings for a military surveillance mission. If altimetry is desired simply for collision avoidance capability (i.e. avoiding a collision with the ground), and altitude determination was to be left to the IMU, then these range and accuracy limitations are not important. However, if accurate altitude measurements are needed at all times, then a small radar altimeter would be required in the place of one sonar module; this would increase the total cost of the vehicle. For very accurate measurements but a large cost increase, a laser altimeter could be considered.

Further details regarding the components and operation of the state and terrain estimation system were not part of the author's design efforts, and so are beyond the scope of this paper.

5.5 Control System

The control system is that part of the S-UAV which allows its motion to be controlled, either by commands from the ground station or by the vehicle itself (for example, in response to a potential collision). The system must be stable and robust, and must be capable of performing within all of the potential missions for the S-UAV. In particular, it must be capable of allowing the vehicle to maintain its position precisely, even in wind, for building inspections. It must be capable of interpreting and responding to data from the state and terrain estimation system, to determine the vehicle's position and velocity, and avoid objects in its path. In addition, it should ideally be "de-coupled," meaning that, for example, a command to pitch should not result in both a pitch and a yaw.

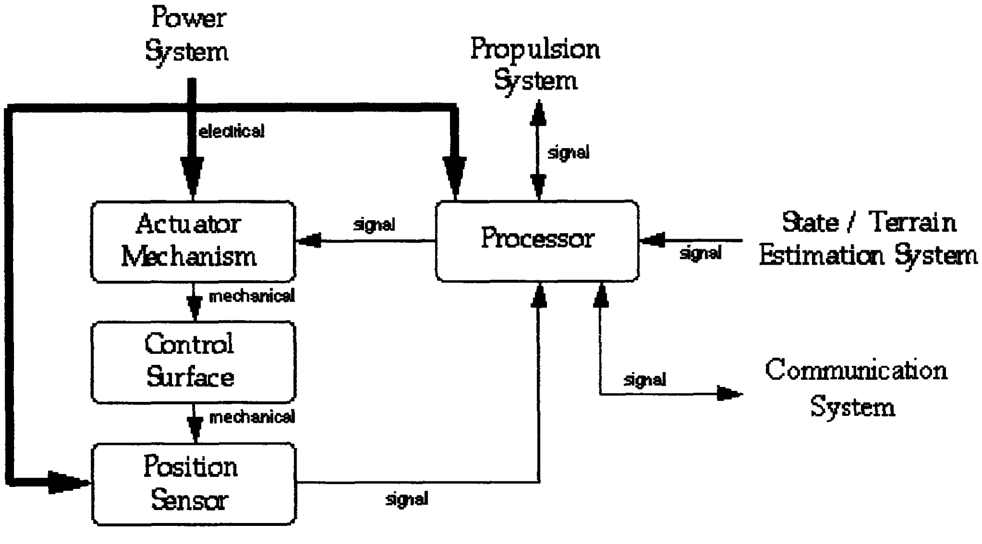


Figure 5.10: Schematic block diagram for the control system

The control system is shown in schematic block diagram form in figure 5.10. The control processor receives commands from the communication system, and data from all of the estimation system (in the form of sonar, GPS and IMU readings)[†], the propulsion system (in the form of rotor RPM readings to measure thrust) and the control surface position sensors. It sends commands to the propulsion system (to increase or decrease thrust) and to the control surface actuators, and information to the communication system to be sent to the ground station. The actuators adjust the control surfaces, which determine the motion of the vehicle and whose positions are measured by the position sensors, in order to provide feedback to the processor.

The details of the control system design can by found in the thesis of team member Young-Rae Kim.

5.6 Propulsion System

It is the responsibility of the propulsion to provide sufficient thrust that the S-UAV may stay aloft. Thus, it must be capable of generating enough power to lift the vehicle over the entire endurance requirement (about 25-30 minutes). As was shown in section 4.4, an electric propulsion system would be optimum given the requirements of the S-UAV, but it proved not to be feasible due to endurance constraints. Instead, a gasoline-powered propulsion system was used.

The propulsion system is shown schematically in figure 5.11. The engine is fed by the fuel tank and controlled by the throttle, which is in turn controlled by the control system. Torque is provided to the rotors through the gear box. The speed of the rotors is measured by the RPM meter, which then sends this information to the control system as feedback.

[†] It should be noted that this processor is the same processor which appears in the SBD for the estimation system, so that there is overlap between the two diagrams.

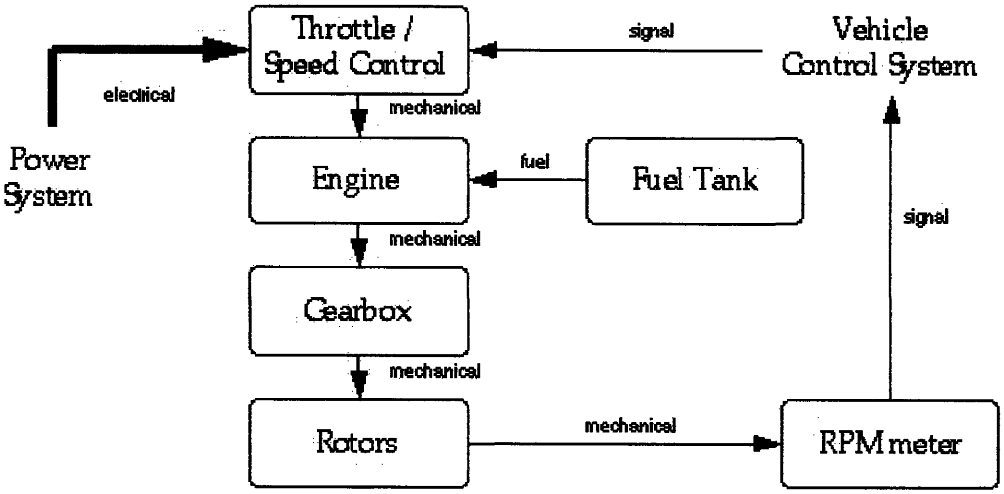


Figure 5.11: Schematic block diagram for the propulsion system

Details of the propulsion system, such as engine and rotor sizing, engine speeds and power requirements can be found in the thesis of team member Arnaldo M. Leon.

5.7 Systems Integration

As is the case with most complex systems, the S-UAV is more than the sum of its parts. However, this synergy comes at a price — the interactions between subsystems which create the greater whole can also give rise to systems integration issues and difficulties that must be dealt with. This is especially true of a system on the size scale of the S-UAV, where the proximity of the components can lead to unique integration problems. This section will attempt to identify and address some of these potential issues.

A problem which can arise when many electrical components are operating in close proximity to one another is electromagnetic interference (EMI). This can become a major difficulty when one of these components is designed to emit electromagnetic waves at a fairly high power level. The radio transmitter on the S-UAV, if designed to operate from behind a downtown building at a range of one kilometer, has an output power of almost two watts (see section 5.1). Although it is difficult to quantify EMI and predict the extent to which other systems will be affected, it was reported in the Draper Small Autonomous Aerial Vehicle team's 1996 report that a radio frequency modem with an output power of two watts was found to interfere with many of the on-board electronics. There are several measures which can be taken to minimize the effects of EMI. First, and perhaps most obvious, a transmitter with a lower output power can be used, although this would require another solution to the line-of-sight problem (see section 5.1). Also, the radio can be located as far away from the other electronics as possible, which was done in the design of the S-UAV (see section 4.5). Since the power of electromagnetic waves falls as the square of the distance travelled, a transmitter located two centimeters away from other electronics (as would be the case if the radio were located in the front of the vehicle) would cause one hundred times the interference of a transmitter located twenty centimeters away. In addition, signals between other electronics, wherever possible, can be carried by twisted pairs rather than single wires. Each member of a twisted pair generates a protective field for the other, and thus both are less susceptible to outside interference. Of course, this involves a trade-off with weight; as was shown in section 4.6, interface weight can be significant, so it might be advantageous to test a configuration using single wires, and replace with twisted pairs only those interfaces which displayed interference problems.

Another issue regarding subsystem interaction which may not immediately be identified is the danger of engine vibrations setting up resonance with the camera shutter, a possibility which was mentioned in section 5.2. The speed of the motor is between 10,000 and 17,000 RPM, which corresponds to a frequency of roughly between $^{1}/_{150}$ and $^{1}/_{300}$ second. This range encompasses popular shutter speeds for cameras, and unless the threat of resonance is recognized, there is a real danger that the exposure time chosen will result in damage to the camera.

Problems with systems integration tend to be very subtle, and are often difficult or impossible to predict without testing. However, it is important to attempt to identify where they might occur and to prevent them in the design stage, to avoid costly re-designs. It is critical to realize that just as synergy can arise from the close interaction of a number of systems, so too can difficulties arise which may not otherwise have been expected.

5.8 Ground Station

Although the design effort in this project was focused primarily on the vehicle itself, the ground station should not be ignored, so its major requirements and features will be discussed briefly here. The ground station is the interface between the S-UAV and its human operator; as such, it should be as simple and easy to use as possible. This is especially true given that the system is designed for a wide range of civilian and military applications and for reasonably low cost; extensive training should not be a prerequisite for operation. To satisfy this requirement, the human interface should be primarily graphical in nature, with perhaps a joystick-style controller and compatibility with a laptop computer.

The station must have a wireless modem of the same type as used on board the vehicle. In particular, the modem's data rate and output power must be equal (or in excess of) those of the on-board modem. In the case of this ground station modem, heat dissipation may require a more complicated design solution than was needed for the S-UAV, since the ground station does not have the luxury of a large air flow so near to the transmitter. In addition, as was mentioned in section 5.1, the ground station requires a parabolic communication antenna one meter in diameter in order to provide sufficient gain to communicate with the S-UAV from beyond line-of-sight.

Though this antenna provides the necessary gain to communicate with the S-UAV, it is not without its problems. Signals which originate from a different location than where an antenna is "pointing" are attenuated; the angle over which the power received is at least half of the maximum power is known as the beamwidth of the antenna. For design purposes, it is often approximated that signals from within the beamwidth are received, and those from outside it are not. For a parabolic antenna of diameter D, the beamwidth θ is given by

$$\theta = \frac{\lambda}{D} \tag{5-9}$$

where λ is the wavelength of the signal. Combining this expression with equation 5-2 for the gain of the antenna yields

$$\theta = \sqrt{\frac{5}{G}} \tag{5-10}$$

Thus, it is clear that as the gain is increased, the beamwidth narrows. For a one meter antenna at 2.4 GHz (0.125 m wavelength), equation 5-9 gives a beamwidth of 0.125 radians, or slightly over 7 degrees. Due to this, the ground station will require some kind of antenna control system to ensure that the antenna is oriented towards the S-UAV at all times. This control system could use information directly from the vehicle's state and terrain estimation system to determine the S-UAV's position relative to the ground, and track it to avoid loss of communication due to inaccurate pointing of the antenna.

To decode the compressed images sent from the imaging system, the ground station must also have a similar chip to the S-UAV's, capable of decompressing JPEG images in real-time at rates of up to 30 fps. This is essential if there is to be no backlog or overload of data, and if the images seen by the on-board camera are to be viewed by the operator in real-time.

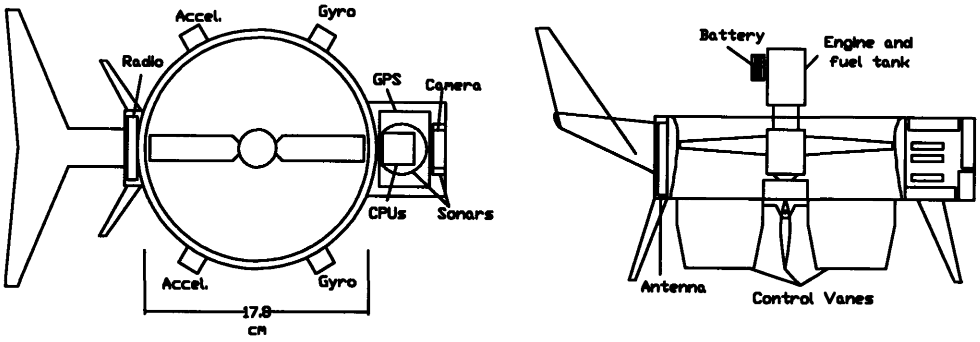
Section 6: Conclusions and Recommendations

The objective of this project was a top-level design of a small unmanned aerial vehicle which would be suitable for both military and civilian applications, at a size which would fill the void between existing UAVs and proposed future military UAVs. Using present-day technology, a small UAV was designed which is capable of performing military surveillance missions, law enforcement missions, news coverage, infrastructure inspection, short search and rescue missions, and environmental studies, and which has a total length of less than one foot. This section will summarize the important characteristics of the S-UAV, discuss possible developments in the future, and conclude with recommendations for further design work.

6.1 Final System Characteristics and Performance

The S-UAV is powered by a single ducted fan, 18 centimeters in diameter, with a tail at the rear, a box for the on-board electronics at the front and control vanes underneath the duct. It is powered by an internal combustion engine located above the duct, with power to the electronics being supplied by a battery. These electronics include a Global Positioning System unit, two sonar ranging modules, an inertial measurement unit, two 486 processors, an image compression chip, a micro CCD camera and a radio frequency wireless modem. The total weight of the vehicle is slightly under 1.5 kilograms. A final configuration figure and performance summary is shown in figure 6.1.

The endurance of the S-UAV is about 25 minutes, and its maximum forward air speed is 30 kilometers per hour in still air. If a line-of-sight with the ground station is not maintained, it has a range of one kilometer; beyond this distance, sufficient power cannot be reliably transmitted to the ground station. If a line-of-sight is maintained, the S-UAV's range increases to over three kilometers; this is not the maximum communication range, but rather the distance



Size: approx. 30 cm x 18 cm x 15 cm

Weight: 1.4 kg

Endurance: 25 minutes

Range: over 3 km line-of-sight
1 km non-LOS

Forward air speed: 0 - 30 km/hr

Vehicle cost: $10,000 US

Operational features: real-time video imaging
autonomous collision avoidance
hovering capability

Figure 6.1: Final configuration and performance

the vehicle can travel at its typical forward speed (assuming adverse wind conditions) before its endurance is exceeded. Because of its configuration, it is capable of hovering with no forward flight speed, and of taking off and landing vertically.

The S-UAV is capable of capturing high resolution visual images at rates approaching full-motion video, and of sending them to the ground station in real-time. It can determine its position and speed, and can detect and avoid objects in its path. Because of the real-time imaging and the collision avoidance capability, the vehicle is very easy to operate; because of its size, it is easy to transport. The price tag on the S-UAV is roughly $10,000.

6.2 The Future of Small UAVs

In the future, perhaps the near future, UAVs on the scale pursued by Lincoln Laboratory, or even on the scale proposed by the RAND report, will be a reality. However, before the "fly on the wall" can move out of the realm of theory, two large technological hurdles must be overcome: propulsion energy density and electronics weight.

As was shown in section 4.4, an electrically-powered small UAV is not feasible with today's battery technology. Luckily, the S-UAV can be made sufficiently large that gasoline propulsion is still practical, and this alternative may be used. For micro-UAVs, though, this is not an option, and they are caught between batteries with insufficient energy density and internal combustion engines which are simply too large. However, a feasible alternative may be presented in the near future in the form of micro-turbines. Under development at MIT, a micro-turbine has the potential to deliver an energy density of 2000 watt-hours per kilogram, dwarfing by almost an order-of-magnitude the energy density of modern lithium ion batteries. Using micro-turbines, the S-UAV could be made with a diameter of less than 10 centimeters, and could weigh only half a kilogram. A complete re-sizing of the S-UAV using micro-turbines can be found in the thesis of team member Arnaldo M. Leon.

The weight and size of the on-board electronics is another limiting factor to the size of a UAV. For the S-UAV, the total weight of the components which are required to perform its missions is over 250 grams, which alone is heavier than an entire micro-UAV. Clearly, this weight must be decreased drastically if micro-UAVs are to incorporate many of the features of the S-UAV, or even if they are to carry out a useful mission. Luckily, microelectronics is a technological field which is developing at an astounding rate, and it may not be long before a complete UAV electronics package can weigh in at 25 grams or less.

Though unavailable today, the technology to construct a micro-UAV is within reach. It is hoped that by designing a UAV using present technology, this project can serve as a useful stepping stone by exposing design considerations and integration issues which may arise once micro-UAVs become reality.

6.3 Recommendations

This top-level design of the S-UAV is a useful beginning to the development of such a vehicle. Before it is to be constructed, however, many more steps must be taken. This section will outline the future which could lie ahead for the S-UAV.

Design is an iterative process. This project was a first run-through of the S-UAV design, and determined much of its configuration and characteristics. However, before moving on the further detailed work, the steps outlined throughout this thesis should be repeated using all the information which was determined during this project. In the next iteration, for example, the capability to hover might be considered a constraint and kept apart from the technical requirements, in the same way as visual imaging capability (see section 3.1). Similarly, a minimum endurance should be considered a constraint. In the Functional Flow diagram, the function "search for optimum communication frequency" is no longer applicable given the spread-spectrum nature of the communication system. When sizing the payload, the mirror system (a late addition to this iteration) should be considered in order to determine its effect, if any, on the sizing of the vehicle itself. These are just a few examples of refinements which can be made now that a first pass at the design has been completed. Once subsequent design iterations are made, with this project as a starting point, assembly and testing can begin.

Testing will play a vital role in the development of the S-UAV. This project has been theoretical and empirical in nature, and it is simply impossible to predict all the problems which may arise once construction and integration actually begin. For example, the wireless modem described in section 5.1 must be built before the exact power requirements, the extent to which it might interfere with the other systems, and other operational characteristics become completely clear. With the ground work which has been laid by this project, assembly and testing could begin before too long, after further design work. The lessons which will be learned through further development will greatly aid the efforts of those working to push the size of UAVs ever smaller; and thus, one of the objectives of the S-UAV will be fulfilled.

This project is the foundation for the development of a small UAV which has the potential to serve in a great many applications. With further design and testing, it could be built using technology that exists today. Perhaps one day soon, police might be more effective, bridge inspectors safer, and news more exciting — thanks to the size and versatility of the S-UAV.

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Appendix: Communication System Heat Transfer Analysis

Here we will determine the equilibrium temperature which will be reached by the radio frequency transmitter which is dissipating a power Q_0. For this analysis, the duct will be modelled as two flat plates, each beginning at x=0 and meeting at x=½πD (D being the diameter of the duct, 17.8 cm). The plates will considered symmetric, so only one will be dealt with. Heat is conducted along the plate, and is lost by convection to the air flow inside the duct. Consider an element of length dx:

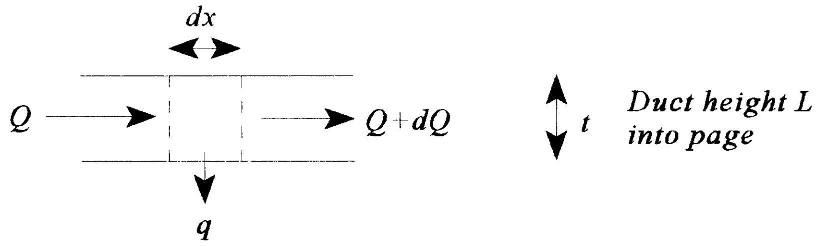

Figure A.1: Heat flow in element of duct length

If the temperature inside dx is T, and the temperature of the air is T_a, we will define the variable θ to be the difference between the two, so $\theta = T - T_a$. The heat conducted into dx is proportional to the local temperature gradient, as per the heat conduction equation:

$$Q = -kA\frac{d\theta}{dx} \tag{A-1}$$

where k is the thermal conductivity of the duct and A is the cross-sectional area of the duct (i.e. A = L times t). Also, from energy conservation (the total heat flow into dx equals the total heat flow out of dx) it is clear that Q = Q + dQ + q, or dQ = -q where q is the heat lost to convection. The heat convection equation is

$$q = h\theta L dx \tag{A-2}$$

where h is the convective heat coefficient. When conservation of energy is applied, it becomes

$$\frac{dQ}{dx} = -hL\theta \tag{A-3}$$

So, combining equations A-1 and A-3 yields two similar differential equations for Q and θ:

$$\frac{d^2Q}{dx^2} = \frac{h}{kt}Q \tag{A-4}$$

$$\frac{d^2\theta}{dx^2} = \frac{h}{kt}\theta \tag{A-5}$$

We will deal first with Q. If we define the variable α where $\alpha^2 = h/kt$, equation A-4 has the general solution

$$Q = A\cosh(\alpha x) + B\sinh(\alpha x) \tag{A-6}$$

where cosh is the hyperbolic cosine function, defined as $\cosh(x) = ½ (e^x + e^{-x})$, and sinh is the hyperbolic sine function, defined as $\sinh(x) = ½ (e^x - e^{-x})$. The constants A and B are found by applying boundary conditions. At x=0, Q must equal $½Q_0$; the radio is located at x=0 and is dissipating power Q_0 in two equal plates. At $x=½\pi D$, the two plates meet and there is no longer anywhere for conducted heat to go, so Q must equal 0. Using these boundary conditions, Q is found as a function of x:

$$Q = \frac{Q_0}{2}[\cosh(\alpha x) - \beta\sinh(\alpha x)] \tag{A-7}$$

where the variable β has been defined as

$$\beta = \frac{\cosh(\frac{\pi}{2}D\alpha)}{\sinh(\frac{\pi}{2}D\alpha)} \qquad or \qquad \beta = \frac{e^{\frac{\pi}{2}D\alpha} + e^{-\frac{\pi}{2}D\alpha}}{e^{\frac{\pi}{2}D\alpha} - e^{-\frac{\pi}{2}D\alpha}} \tag{A-8}$$

Now we turn our attention to θ. Equation A-5 has a similar solution to that for equation A-4:

$$\theta = C\cosh(\alpha x) + D\sinh(\alpha x) \tag{A-9}$$

Instead of applying boundary conditions to find the constants C and D, we can substitute our expressions for Q and θ into equation A-3 to get

$$\frac{Q_0}{2}\alpha[\sinh(\alpha x) - \beta\cosh(\alpha x)] = -hL[C\cosh(\alpha x) + D\sinh(\alpha x)] \tag{A-10}$$

Since this relation must hold true for any value of x, it must be the case that the cosh(αx) terms are equal and that the sinh(αx) terms are also equal. Thus, we find that

$$C = \frac{Q_0\alpha\beta}{2hL} \qquad and \qquad D = -\frac{Q_0\alpha}{2hL} \tag{A-11}$$

and so

$$\theta = \frac{Q_0\alpha}{2hL}[\beta\cosh(\alpha x) - \sinh(\alpha x)] \tag{A-12}$$

What we are interested in is the temperature of the radio, which in this model is assumed to be equal to the temperature at x=0. This temperature is

$$\theta(x=0) = \frac{Q_0\alpha\beta}{2hL} \tag{A-13}$$

All the values in equation A-13 are now known explicitly, except for the convection coefficient h. For laminar air flow over a flat plate, Burmeister (p. 287) gives an expression for the Nusselt number in terms of the Reynolds and Prandtl numbers:

$$Nu = \frac{hL}{k_a} = 0.664 Re^{1/2} Pr^{1/3} \tag{A-14}$$

where k_a is the thermal conductivity of the air, the Reynolds number is Re = vL/ν (v = velocity of the flow and ν = kinematic viscosity of air) and the Prandtl number for air is 0.7.

Now everything is known, and θ at the radio transmitter can be found. For an aluminum duct (k=132 Btu/hr-ft-°F, from Chapman) 1.5 cm thick, 6.5 cm high and 17.8 cm in diameter, air flowing at 24 m/s (Leon) with properties evaluated at 80 °F (from Chapman), and a transmitter dissipating 28 W of heat, the value of θ is 15.5 °C. Thus, if the temperature of the ambient air is taken to be 20 °C, the equilibrium temperature achieved by the radio is 35.5 °C.