Preliminary Weight Sizing and Configuration Layout for a Small Unmanned Aerial Vehicle (S-UAV)

by

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Nomenclature

Symbol	Description	Units
A_e	Exit area of streamtube	m^2
A_R	Area of rotor disk	m^2
c_p	Specific fuel consumption	g/hr/W
D	Drag	g, N
D_{rotor}	Rotor diameter	cm
E_{loiter}	Mission loiter time	hr
f	Equivalent flat plate drag area	m^2
K_{drag}	f/A_R	~
$K_{structure}$	Factor to account for structural weight	~
P_{com}	Power required to communicate	W
$P_{electrical}$	Power required by all electrical systems	W
P_{motor}	Power output of the motor	W
P_{req}	Power required to hover	W
R	Range	km
R_N	Reynolds number	~
T	Thrust	g, N
V_e	Exit velocity of jet	m/s
V_{fwd}	Forward velocity	m/s
V_o	Inlet velocity normal to rotor disk	m/s
W_{batt}	Weight of battery	g
W_{fuel}	Weight of fuel	g
W_{motor}	Weight of motors	g
$W_{systems}$	Weight of electrical systems	g
W_{total}	Total weight	g
$\eta_{alternator}$	Alternator efficiency	~
η_{gear}	Gearbox efficiency	~
η_p	Propulsive efficiency	~
ρ	Air density	kg/m^3
ρ_p	Batter power density	W-hr/kg
σ	Diffuser ratio	~

Acronym	Description
DARPA	Defense Advanced Research Projects Agency
RFP	Request for Proposals
μUAV	Micro Unmanned Aerial Vehicle
UAV	Unmanned Aerial Vehicle
IC	Internal Combustion
IR	Infra-Red
UV	Ultra-Violet
CPU	Central Processing Unit
RPV	Remotely Piloted Vehicle
KE	Kinetic Energy
QFD	Quality Function Deployment
S-UAV	Small Unmanned Aerial Vehicle
DSAAV	Draper Small Autonomous Aerial Vehicle
GPS	Global Positioning System
IMU	Inertial Measurement Unit
DGPS	Differential Global Positioning System
R/C	Radio Controlled
GNC	Guidance, Navigation and Control

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Chapter 1

Background on the S-UAV Concept

1.1. The DARPA Request for Proposals and the RAND Study

During the summer of 1996, The Defense Advanced Research Projects Agency (DARPA) issued a request for proposals (RFP) calling for the design of a Micro Unmanned Aerial Vehicle (μUAV). This new vehicle should be orders-of-magnitude smaller than current UAV systems, and to be available within a 3-year technological horizon. The primary mission for the μUAV would be to perform forward military surveillance for a small team of soldiers (such as Navy SEALs) or other useful military missions [Thrinh]. The data obtainable from μUAV-mounted sensors would be real-time and accessible virtually on-demand. Satellite or high-altitude aircraft platforms simply cannot provide this ease of accessibility, and current-size UAV systems are too large, bulky, expensive and detectable for this type of proposed scenario.

In response to the RFP, a preliminary design study [White] was performed by the RAND group, describing some possibilities for technologically far-term μUAV configurations. One configuration consisted of a ~1.5 cm vehicle with a weight of about 1 gram and a cruise speed of about 40 km/hr (R_N = 12,000). The power required by such a vehicle is on the order of 250 mW. An even smaller configuration was dimensioned to the order of about 0.1 millimeters, with a weight of about 1.0 μgram. A power system producing 35 nW would be able to provide lift and a forward speed of about 8 km/hr. This vehicle would have a cruise Reynolds number of about 10, comparable to some microscopic organisms. At these small sizes, the only feasible and practical configurations are those that are hover-capable to some extent.

The major benefit for this type of miniaturization technology is the potential for mass production, quite possibly on the order of millions, reducing costs drastically. These machines would also be practically undetectable and impossible to eliminate completely. A typical mission would involve squadrons of several hundreds or thousands, all working together to complete a mission. To extend the communications range, these mini-squadrons could possibly use each other as communication relays to a fixed or mobile, portable ground station. Also, the range of these small aircraft could be extended by transporting them in the payload bays of some of the slightly larger UAV's.

1.2 Advantages of Very Small UAV Systems

The most unique operational advantage of small UAV systems is the ability to access very hard-to-reach areas, such as ventilation shafts, pipes, towers, enclosed structures, etc. Their small size also makes them virtually undetectable, and if used in great numbers, impossible to eliminate completely. Additionally, although not yet proven, there is also some potential (2 orders-of-magnitude) for reduced ground support and life cycle costs as well.

In the civilian market of today, a major selling benefit is the S-UAV's minimum liability in crashes and accidents. Any impact damage would be almost negligible should one fall from the sky and collide with an automobile, for instance. This is definitely not the case for a 150 mph, 200 pound conventional UAV. Such liability issues effectively prohibit the use of large UAV's in any widespread commercial market.

Small UAV's also share other advantages common to all UAV systems: an ability for operational persistence, the elimination of human risk in the mission, ease of disposability, and a very strong industry support and interest for research and development.

1.3 Lessons Learned from the Draper SAAV

The Draper/MIT/BU team submitted an entry and won the 1996 International Aerial Robotics Competition, held in Florida. Fully autonomous helicopter flight from takeoff to landing was demonstrated for the first time in competition history [DeBitetto]. Their vehicle (figure 1.1), known as the Draper Small Autonomous Aerial Vehicle (DSAAV), served as a testbed for the enabling technologies required for an intelligent surveillance vehicle. It was suggested that, in a military role, the vehicle could provide troop and enemy forces reconnaissance in urban environments, and detect and identify military obstacles. It could also be used for sensor placement and for serving as a communications relay.

Figure 1.1. The 1996 Draper SAAV [DeBitetto].

The navigation system (figure 1.2) of the Draper SAAV consisted of an extended Kalman filter integrating measurements from a differential GPS receiver, an off-the-shelf inertial measurement unit (IMU), an ultrasonic altimeter, and a magnetic flux compass. An on-board camera and video transmission system allowed for real-time image processing from the ground station. The vision recognition algorithm was successful in finding and identifying the required competition targets. Fully autonomous takeoffs, landings, and way-point navigation were demonstrated in the competition.

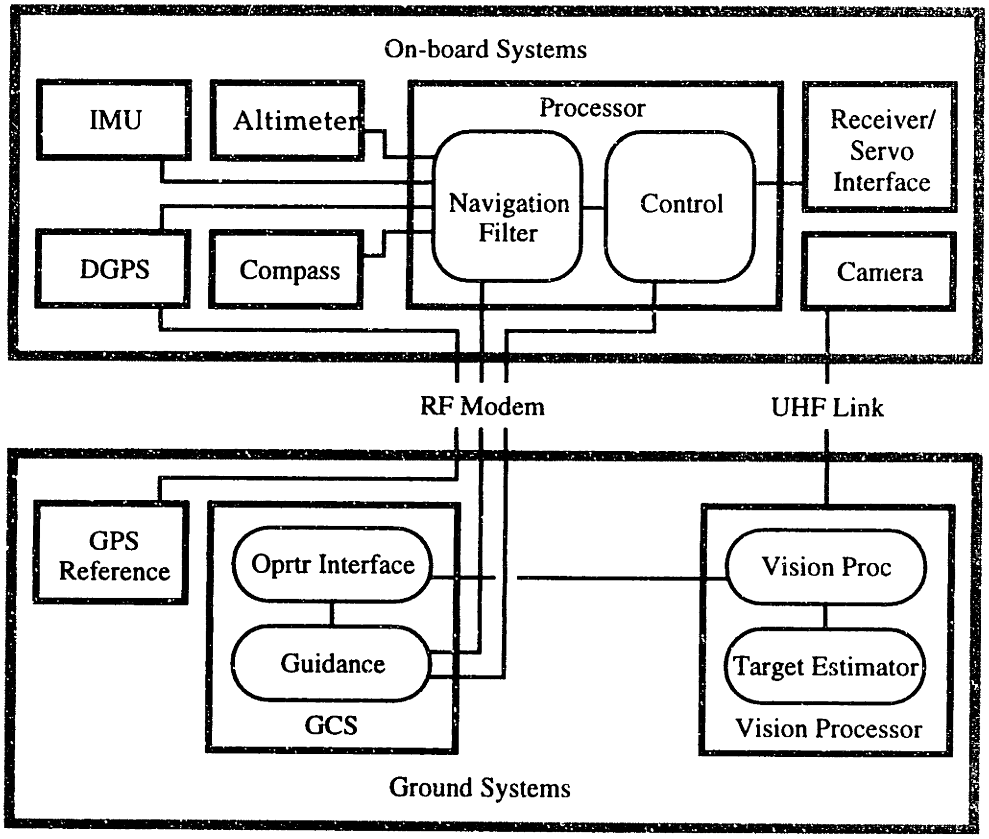


Figure 1.2 Schematic Block Diagram for the Draper SAAV [DeBitetto].

It was found from competition that for increased functionality, fully autonomous flight may not be what is needed. Instead, the operation of the helicopter should be simple enough to allow "point and click" or "joystick" operation. A robust flight control system capable of rejecting strong gust disturbances is critical, along with a active on-board collision avoidance system, to prevent the vehicle from crashing into the ground, buildings, trees, towers, or other UAV's.

Chapter 2

Potential Civilian Markets for a Small UAV System

2.1 Possible Uses for a S-UAV in the Civilian Markets

Besides the more obvious military missions, there are several civilian missions uniquely applicable to small UAV systems. These vehicles may find use as small, inexpensive, portable communications relays for cellular phone and internet communications. Another possible role is that of a "carrier pigeon." Small packages could be sent across the city, delivered right into moving cars through the sunroof, for example. Also, the new technologies could most certainly complement the rapidly-growing and ever-more sophisticated R/C model hobby, which has played a major role in the development and progress of UAV systems themselves. In another role, a modest fleet of small UAV's could be used in much the same way R/C dirigibles are used today: towing banners or other promotional displays inside sport arenas, terminal stations, airports, and shopping malls, as well as outside in ski resorts, parks, and beaches.

These vehicles could also have less commercial uses. The small size of these units make it an ideal scientific payload platform for planetary explorations to other worlds with atmospheres, such Mars, Titan, Jupiter, etc. This mission scenario is analogous to the one for the 1996 Mars Pathfinder R/C ground rover. Other missions considered to be the most feasible are as follows:

Surveillance and Law Enforcement - (the "flying security camera") The main benefits for this market are low observability and a good vantage point. These UAV's are not confined to a fixed observation location, permitting search and tracking capabilities. Possible markets include drug interdiction, and border/casino/parking lot monitoring. The small size also allows for access through ventilation ducts and through doors, windows, mailboxes, etc.

Search and Rescue - the UAV could play a part in disaster area appraisal, early warning service, or search and rescue. Ski resorts could have a small fleet of autonomous drones doing routine surveillance of the slopes. They could also give data on local weather conditions. Novice or child skiers could be given a small homing device which can be activated in case of emergency. The UAV could find the downed skier and transmit real-time visual, IR, and audio data ("flying walkie-talkie") back to the ski patrol cabin. In this way, they could have an immediate assessment of the situation so as to know what type of equipment to haul up the slopes with their snowmobiles.

Firemen in burning buildings could use a S-UAV to inspect rooms without having to actually go into them and search for trapped people. A short flight over the burning area will quickly reveal where the smoke and fire is originating from. Also, it could help firemen search for the occasional person trapped inside a ventilation duct. A small UAV could also take rescue lines from the shore to drowning people or ships during storms.

Facility and Infrastructure Inspection - large structures such as buildings and bridges are very difficult and dangerous to inspect at their required intervals for corrosion, damage, and irregularities (like woodpecker holes bored through a shuttle main tank's insulation). Examples of such tasks include overseeing the stacking of rocket engines, inspecting guy wires on large towers, inspection the exterior hull of a ship for corrosion (even at high sea), and inspection of oil rigs, bridges, and skyscrapers. It is even possible to be able to inspect the inside of a fuel tank of a large vessel by flying in through the fuel cap, as well as inspection the inside of sewers and underground water tanks and silos.

A S-UAV could be equipped with high-quality 3-D visual, IR, and UV cameras to allow scrutinizing inspection. Some acoustical sensors and perhaps a small "poker" or arm could be incorporated. These images could be fed to a virtual-reality headgear, and the motions of the UAV could be controlled by a special body suit that sends flight commands based on the body movements of the operator. This would provide the most interactive method of control possible.

Environmental Studies - the main benefits to the end-user here are good accessibility and potential for low cost. This would allow close observation of bird's nests or volcanoes. It could go into foxholes, trenches, underground installations, and other hard to reach areas (like Egyptian tombs). Another use could be to sample the air above a freeway, trying to get an idea of what happens to the exhaust from the automobiles. This apparently is still a big mystery in the field [Bromhal]. It could follow pollution plumes while measuring airborne concentrations of different gasses; it could go inside smoke stacks. It could be used for assessment of hazardous environments, such as those following chemical or nuclear accidents. The UAV could inspect wildlife and forests. Coordinated arrays of S-UAV's could study larger atmospheric phenomena, like tornadoes. Plotting bird migratory paths may be possible as well.

2.2 List of Contacts for the Preliminary Marketing Survey

As part of a preliminary marketing survey, the following organizations were contacted. Personnel in these organizations were then interviewed about their jobs, and if a S-UAV system could be beneficial to them.

- WBZ-AM News Radio - Metro Traffic
- Aerial Buckets - Boom Trucks Dealer
- Moller International - UAV Systems
- Wachussets Mountain Park - Ski Patrol
- MIT Soaring Association
- Department of Earth, Atmospheric, and Planetary Sciences
- MIT Police Department

2.3 Summary of Customer Feedback

Search and Rescue - according to the ski patrol personnel interviewed, a search and rescue UAV would be more useful and economical on the larger slopes, since the smaller slopes are very easy to patrol. Currently, the standard procedure for rescuing a downed skier is as follows: a downed skier is found by the ski patrol and then the snowmobiles at base are radioed in for help. The snowmobile then heads up the slope and performs a pattern search for the downed skier. Sometimes it can take more than an hour to find an injured skier.

An UAV system would be indispensable during post-avalanche search and rescue, when most ski patrols are very reluctant to enter the avalanche zone. Again, it is the larger skiing resorts that frequently have this problem. If the UAV system can show a potential for reduction in manpower and add an extra margin of safety to the operations, then the system may be a truly viable option for ski resorts.

Facility and Infrastructure Inspection - the conversations with Moller International dealt mainly on their Aerobot RPV, which is not a major focus of their company. The main use of their RPV is for the inspection of elevated structures, such as bridges and towers, and most of their funding is obtained from the California Department of Transportation (CalTran) and the Department of Defense. The Navy and Air Force also showed interest in the project. The proposed military mission was to fly out 10 km, land and listen, take off again, move 10 km, land, sit and listen for 24 more hours. Then it could return to the home base, typically a Hum-Vee.

Another potential market Moller investigated was the news media, but they discovered there is a very serious liability and insurance problem. Simply stated, nobody wants a 50-100 lb. vehicle flying over their heads without a pilot in it. The liability risks inherent in such a system would instantly kill any civilian UAV project, unless the vehicle is small enough not to inflict major damage. Some professional pilots also expressed concern about collision with commercial UAV's. They would consider the system safe if, and only if, the impact of a S-UAV would cause no greater damage than bird strikes.

Also along the lines of infrastructure inspection, the inspection of bridges is carried out using a 3-part boom, which costs about $1500 per day to operate. Small UAV's may be able to bring this cost down, and thus enter the market. On the other hand, most boom trucks are used for the inspection of and work on electrical poles and trees. This implies that a S-UAV meant for such a role is useless without some sort of mechanical arms.

Search and Rescue - security service companies suggested that instead of having small UAV's patrol an area, it is much better to have a human guard on duty. A guard is much more able to respond to situations quickly.

When asked about the use of S-UAV's, police officers suggested that a hovering capability is required because they might want to take a look at a specific spot in detail. Some type of remote control and video system is also required. They envision small UAV's as able to fly very quietly, searching and tracking a fugitive, much like full-size police helicopters. An infrared camera is necessary for night missions.

The size of the UAV depends heavily on the application. Small size is beneficial in case they want to get inside a building. Sometimes, small size is not really necessary. A real mission would most likely use small UAV's in conjunction with "full size" UAV's.

In essence, cost is a major driving factor. Most people interviewed responded that they cannot justify using such a system unless it is extremely cheap, compared to other equipment that does the same job. Conversely, the use of larger UAV's in city environments, surrounded by buildings and people, is subject to very serious liability and safe controllability problems. Combining and taking advantage of the features of a S-UAV (small mass, potential low cost, and low speeds) may open a window of opportunity for such a vehicle.

Chapter 3

Deriving the Civilian-Military Customer Requirements

3.1 Deriving and Ranking the Customer Requirements

The market survey described in the previous chapter produced 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 purpose of a requirements analysis. First, all the different needs of all the 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 practical to design to a broader total market; this required some 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.

3.2 Prioritization of Customer Needs

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. Table 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 chapter 2. Included as well is a column for a military surveillance or reconnaissance mission, such as is the focus of the Lincoln Laboratory's micro-UAV's. 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 totaled on the right of the table, and then normalized to a weighting out of ten.

The SUAV must be / must have :	MARKET / MISSION							Total Importance	Relative Importance
	Police	Military	Inspection	News	S&R	Boating	Mapping		
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

Table 3.1. Sorting and Ranking of the Customer Needs.

It is important to note that the need for a basic imaging camera does not appear in table 3.1. Of the potential missions listed, 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 table 3.1 represent characteristics which are tradable regardless of their importance; visual imaging capability simply cannot be among them.

It is clear that operational considerations - particularly ease of use 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 construct a prioritized list of technical requirements by using a QFD matrix, as seen in figure 3.1.

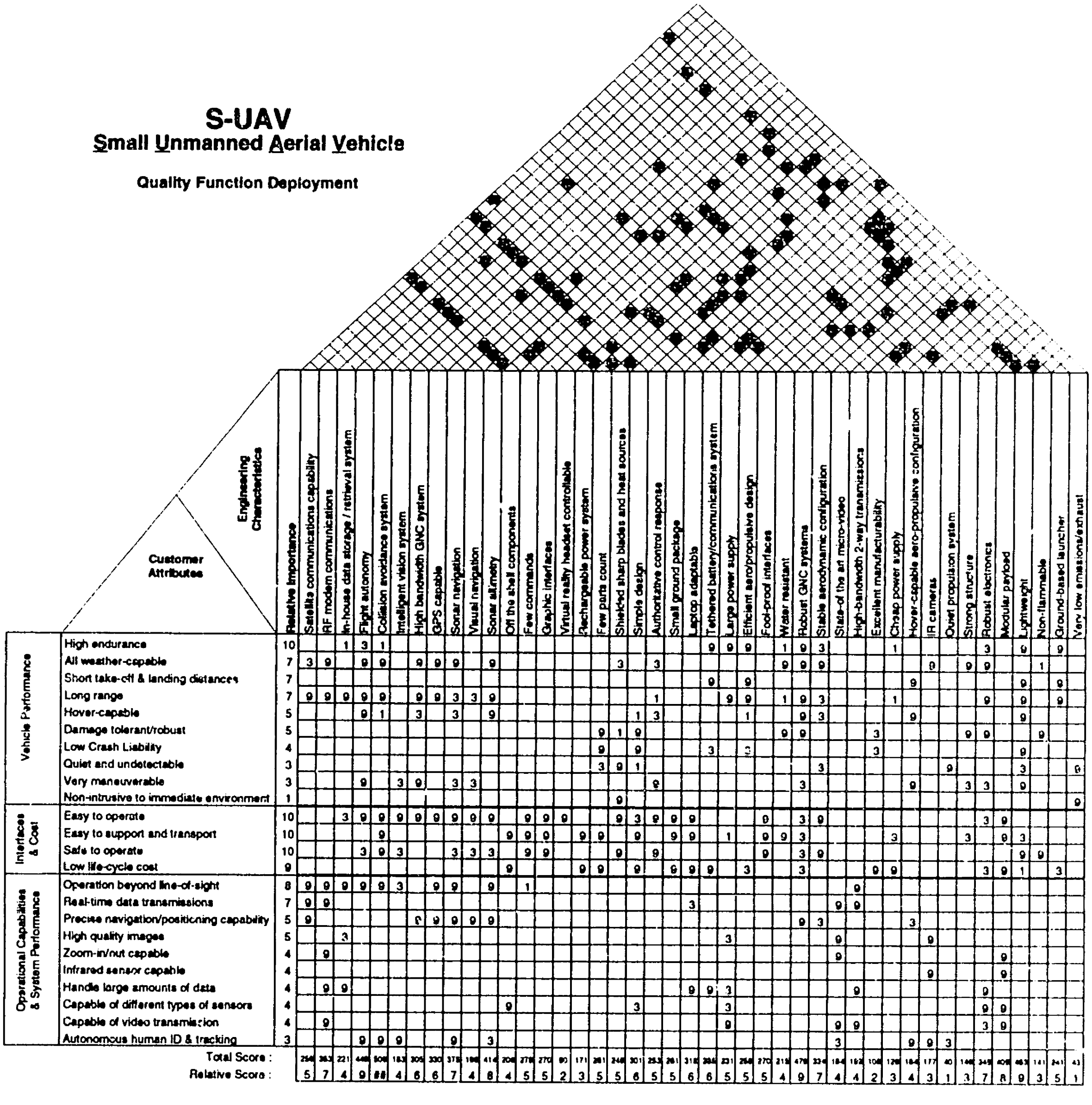


Figure 3.1. The Quality Function Deployment Matrix for the S-UAV.

3.3 Deriving the Technical Requirements

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 accountability of these requirements to the customer's original needs.

The QFD matrix for the S-UAV is shown in figure 3.1. Down the left side of the matrix are the customer needs, 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 before; 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 the triangular "roof" which sits atop the matrix, potential conflicts between requirements are identified.

3.4 Technical Requirements and Conflicts

When the relative scores of the technical characteristics for the S-UAV are calculated, six particular requirements receive scores of eight or greater. The sorted list of derived technical requirements can be seen in table 3.2, the most important technical requirements are listed below:

- Collision avoidance system
- Robust GN&C system
- KE less than R/C glider
- Flight autonomy
- Altimetry
- Modular payload

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

Other important features were "GPS capability", and a "stable aerodynamic configuration" to provide a solid platform for guidance and control. Most of the other features had to do with simplifying the user-interface, such as "few commands" and "fool-proof interfaces." Simplicity in the design is needed, by reducing parts count and by using off-the-shelf components. Some sort of safety to the end user must be incorporated in the sense of protection from spinning blades and heat sources. Good quality communications is desired, provided by high bandwidth communications systems and internal data storage and retrieval, with the possibility of using satellite communication links as well.

CRITICAL Technical Requirements	Score
Collision avoidance system	10
Robust GNC systems	9
KE less than R/C glider	9
Flight autonomy	9
Sonar altimetry	8
Modular payload	8
Sonar navigation	7
RF modem communications	7
Robust electronics	7

MAJOR Technical Requirements	Score
Stable aerodynamic configuration	7
GPS capable	6
Laptop adaptable	6
GNC system faster than 40 Hz	6
Use only proven designs	6
Tethered battery/communications system	6
Few commands	5
Graphic interfaces	5
Fool-proof interfaces	5
Minimize parts count as much as possible	5
Ground station must fit in PC laptop	5
Fuel efficient aero/propulsive design	5
Authoritative control response	5
Satellite communications capability	5
Shielded sharp blades and heat sources	5
Ground-based launcher	5
Large power supply	5
In-house data storage / retrieval system	4
Water resistant	4
Off the shelf components	4
High-bandwidth 2-way transmissions	4

MINOR Technical Requirements	Score
Visual navigation	4
State-of the art micro-video	4
Hover-capable aero-propulsive configuration	4
Intelligent vision system	4
IR cameras	3
Rechargeable power system	3
Structure must withstand 40 km/hr impact	3
Non-flammable	3
Fuel/power source must be inexpensive	3
Excellent manufacturability	2
Virtual reality headset controllable	2
Exhausts must not contaminate measured data	1
Engine/rotors must not be heard over 200+ ft	1

Table 3.2. List of Sorted Technical Requirements for the S-UAV.

In the QFD matrix, a few potential conflicts were identified which occurred between two highly-rated requirements. The requirement for light weight (low KE) 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.

Some of the less important technical requirements show areas which do not need special attention. These can be dismissed if they prove to be too impractical since they provide very little value to the customer. Infra Red camera equipment and state-of-the-art vision systems and algorithms were not really mission critical. This can save some weight and complexity, since any simple commercial CCD camera will do the job. Note that the environmental concerns, i.e. low noise and exhaust, came in near the end, as well as manufacturability. This was unexpected, specially since some missions did seem to require covertness.

Chapter 4

The Design Concept

4.1 Focus of the MEng / Lincoln Labs S-UAV Design Project

Lincoln Laboratories is currently working on the design of a fixed-wing small UAV configuration in response to the potential future needs of the US armed forces. The wingspan of their proposed vehicle is on the order of about 6 inches, and is to be powered by batteries. A simple 3-view of a possible vehicle configuration is shown in figure 4.1.

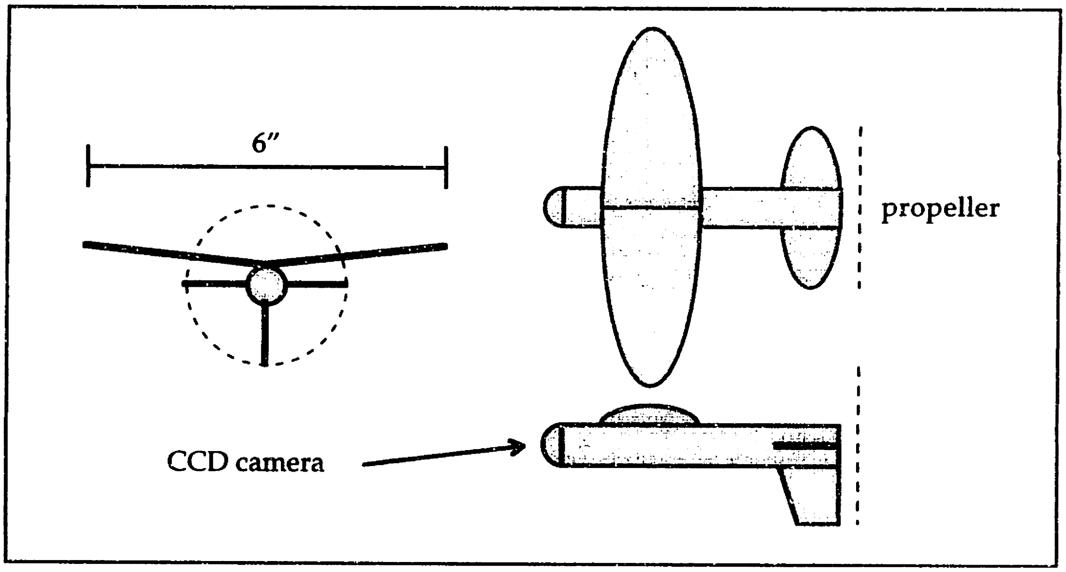


Figure 4.1. Three-View of the Lincoln Laboratories Micro-UAV Prototype.

Current technology cannot meet the demands of the RAND designs for μUAV's. If fact, it is not really known if such a small UAV would be of any use in reality. Another potential market niche exists just above the μUAV, the S-UAV market, with characteristic size in the 0.5 - 1.0 m scale. This was chosen as the major focus for the MEng project: a stepping stone between what exists today and what will exist in the future. This is characterized in figure 4.2.

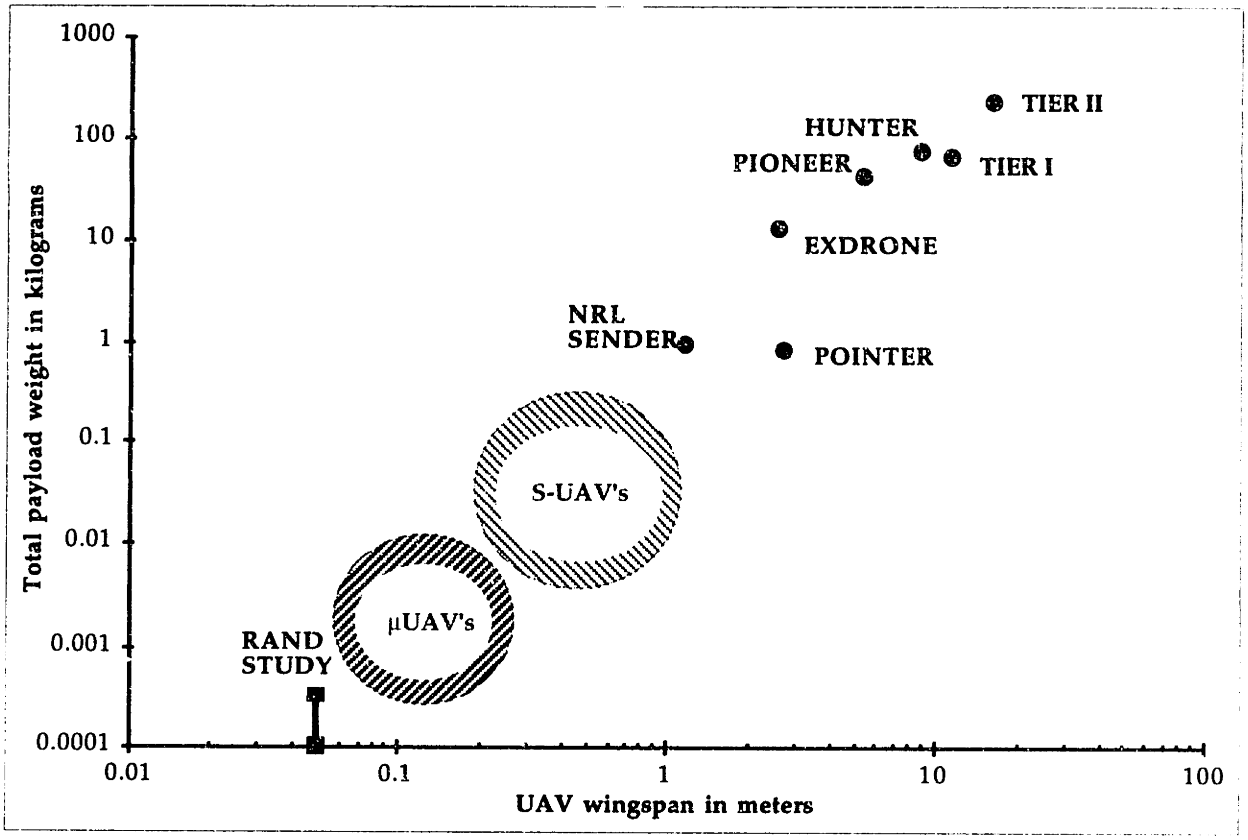


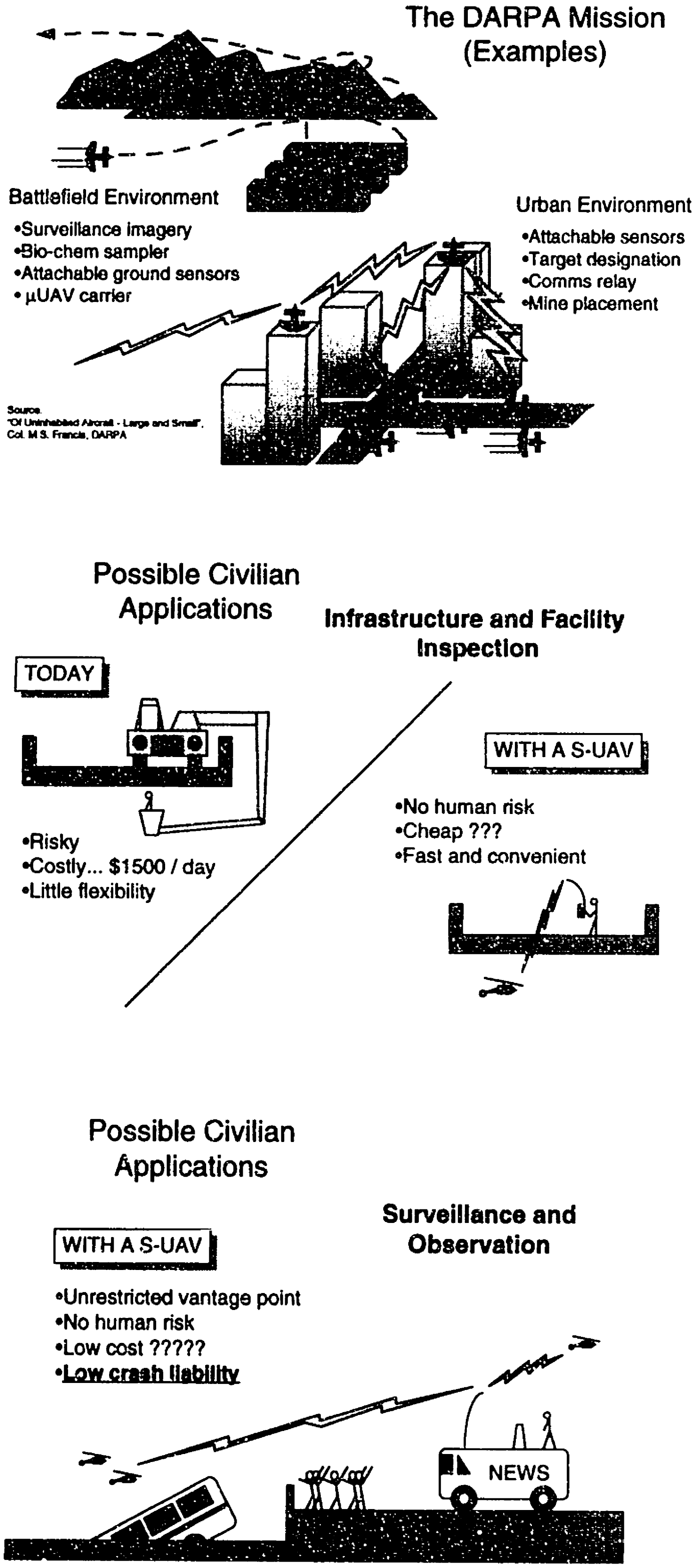
Figure 4.2. Existing and Future Dimensions of UAV's.

4.2 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 envisioned in chapter 2. 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 which are performance characteristics 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 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 images taken. Some of these mission scenarios are shown in figure 4.3.

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 high-g turn. These mission profiles can then be used later in the design, to ensure that the performance requirements (point or otherwise) are met.



Source:
"Of Uninhabited Aircraft - Large and Small",
Col. M.S. Francis, DARPA

Figure 4.3. Some Proposed Mission Scenarios.

4.3 Configuration Decision Tree for the S-UAV

Now that a mission and a size niche for the vehicle has been determined, a good configuration layout for the S-UAV needs to be determined. This can be done with a configuration downselect as shown in figure 4.4. While going through the down select, all decisions made must reflect on the requirements derived in chapter 3.

First, should the configuration be fixed-wing, or should it have some type of hovering rotor? As the UAV becomes smaller, it becomes increasingly difficult to allocate the wing area required for very slow flight. Slow flight, even hovering flight, is critical to some of the inspection mission scenarios, such as infrastructure inspection and interior flying. So a hovering configuration is chosen for the S-UAV. A hovering configuration is best achieved by the use of a hover fan. This fan can be either free-tip or enclosed in a duct. Although a free-tip rotor does without the added weight of the duct, the disk area has to be about 140% larger than a ducted fan, for the same amount of thrust. A free-tip rotor also reduces the safety of the design, and makes it awkward to handle. For this reason, only ducted fan configurations are considered.

Once the required rotor disk area is established, it is shown from disk momentum theory, that a high disk solidity ratio is desired. This establishes the need for a multiple wide-chord blades. Thus a 3-4 bladed configuration is more favorable than a 2-bladed rotor configuration, even though there is a weight and complexity penalty involved.

Given the required disk area needed for flight, it is possible to split this area into multiple fans. This is not really advantageous because the efficiency (Thrust/Power ratio) of the system decreases, and the complexity increases. Therefore, for any hovering configuration, a minimum number of fans should be used. There are also many ways to cancel the torque created by the rotor. It was decided that using counter-rotating blades may offer a good compromise.

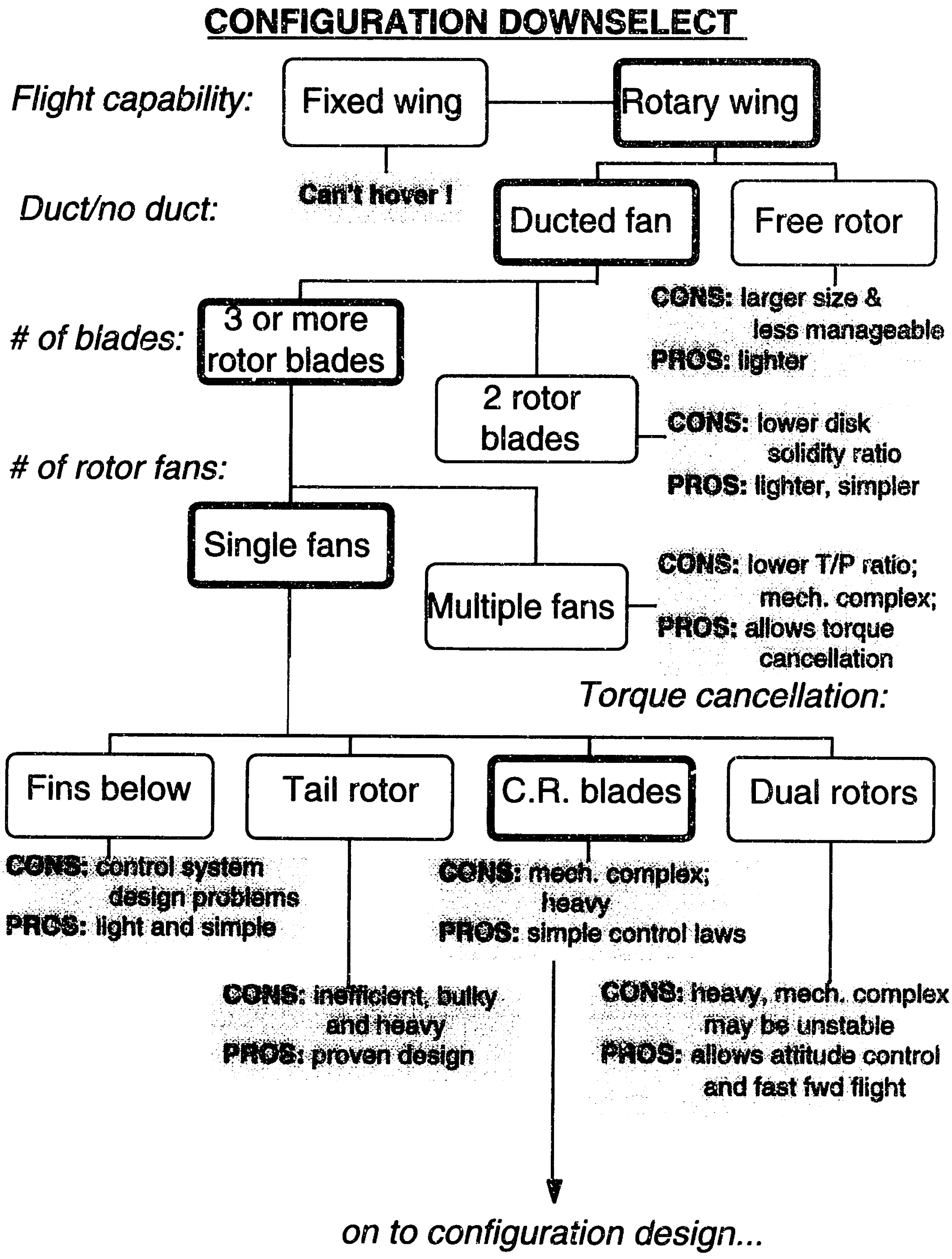


Figure 4.4. Decision Tree for the S-UAV.

Chapter 5

Preliminary Weight Sizing

5.1 Power Required to Lift and Propel a System of a Given Weight

For preliminary weight sizing calculations, the fan/rotor can be modeled as a disk momentum generator [Kohlman, McCormick] as shown in Figure 5.1. From disk-momentum theory, the total power required (P_{req})to produce a given thrust (T) is given by equations (5.1) and (5.2),

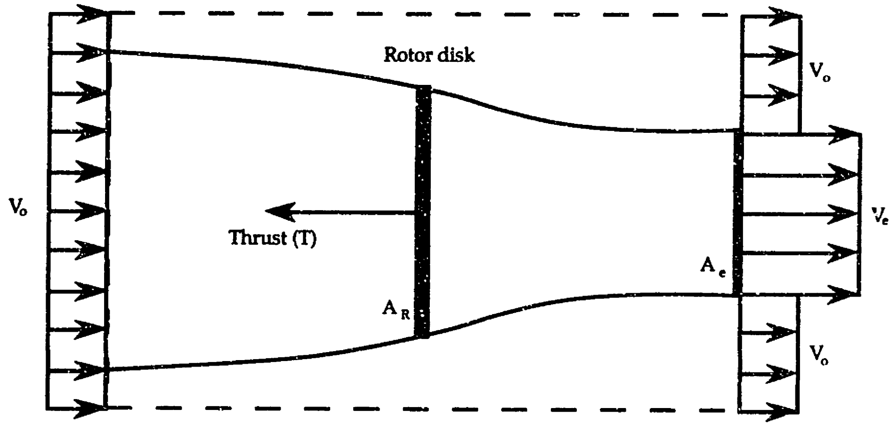


Figure 5.1. The Basic Actuator Disk from Momentum Theory.

$$P_{req} = \frac{T}{\eta_p \eta_{gear}} \left(\frac{V_e + V_o}{2} \right) \tag{5.1}$$

$$T = \rho A_R V_e \sigma (V_e - V_o) \tag{5.2}$$

where η_p is a rotor efficiency factor to account for viscosity losses, obstructions behind the rotor disk, blade airfoil L/D, and rotor tip losses. This value is assumed to be $\eta_p = 0.70$. The η_{gear} efficiency factor accounts for mechanical transmission losses. Suitable values are listed below [Roskam]. The actual value used would correspond to the final S-UAV configuration design described in chapter 8.

Configuration	η_{gear}
Direct drive installation	1.00
Simple gearbox	0.92
Counter rotating blades	0.87

The diffuser ratio, σ, is defined as the area of the exit disk to the area of the rotor disk:

$$\sigma = \frac{A_e}{A_R} \tag{5.3}$$

From actuator disk theory, $\sigma = 0.5$ for a free-tip rotor in hover (highly loaded disk). A straight duct of sufficient length around the rotor can increase the diffuser ratio to a value of 1.0 in hover, thus reducing the power required for a given thrust. By increasing the diffuser ratio further, the increased adverse pressure gradient on the inner surfaces will cause the flow to separate, imposing a practical upper limit on σ. The V_o term is defined as the freestream velocity component normal to the plane of the rotor disk. After solving for V_e and combining (5.1) and (5.2), a method to find the power required to produce a certain thrust is found from:

$$P_{req} = \frac{T}{2\eta_p \eta_{gear}} \left(\frac{3V_o}{2} + \sqrt{\frac{V_o^2}{4} + \frac{T}{\rho A_R \sigma}} \right) \tag{5.4}$$

By tilting the rotor disk, the thrust produced can both be used to provide lift and forward velocity. This is illustrated in figure 5.2.

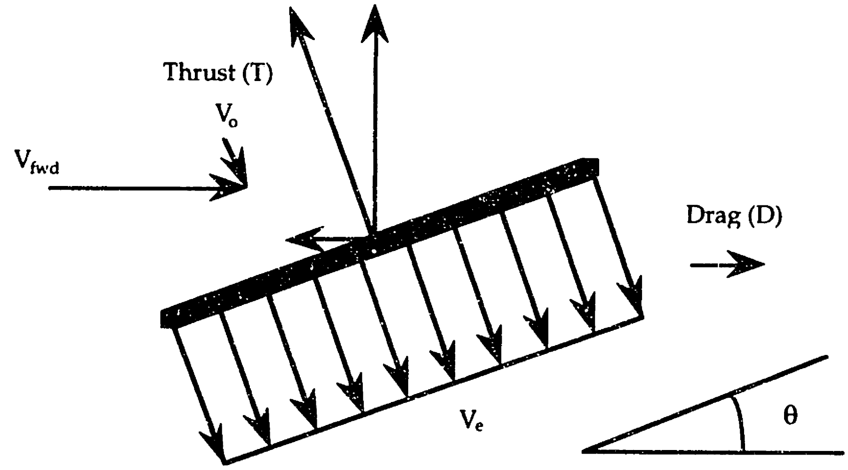


Figure 5.2. Schematic of a Tilted Rotor.

It can be easily shown that the flow velocity normal to the rotor disk (V_o) and the total thrust desired (T) is given by:

$$V_o = \frac{\rho V_{fwd}^3 f}{2T} \tag{5.5}$$

$$T = \sqrt{W_{total}^2 + \left(\frac{\rho}{2} V_{fwd}^2 f \right)^2} \tag{5.6}$$

where f is the equivalent flat plate drag area of the entire vehicle during forward flight, and the forward flight velocity (V_{fwd}) is prescribed by the mission requirements. The drag area (f) term is rather difficult to estimate during preliminary design without actually designing the vehicle first. The problem is compounded if the configuration is a hovering ducted fan, since most of the flow will not be attached during forward flight. A quick, but probably not optimal, method to estimate f, is to assume that it is directly proportional to the rotor disk area. In this manner, one can assume that:

$$f = K_{drag} A_R \tag{5.7}$$

For the weight sizing calculations, K_{drag} was assumed to be 0.25.

5.2 Total System Weight Required to Produce a Given Power

Equation 5.4 can be used to find the power required to lift a certain weight: one equation, with two unknowns. To solve the system, another equation that the finds the weight of a S-UAV capable of producing a certain amount of power is needed. One simple model is the following:

$$W_{total} = K_{structure}\left(W_{motor} + W_{batt} + W_{systems} + W_{fuel}\right) \tag{5.8}$$

where

$$W_{batt} = W_{batt-comms} + W_{batt-systems} + W_{batt-motor} \tag{5.9}$$

where $K_{structure}$ is constant to account for the structural weight, which is assumed to increase linearly with the weight of all the other components . For a first iteration, $K_{structure}$ was set to 1.80. Note that weight also accounts for gearboxes, rotor blades, landing gear, fuel tanks, etc. After some preliminary structural design calculations are done, a more accurate value should be derived, and the weight sizing should be reiterated.

To find W_{motor}: The weight of an engine (either internal combustion or electric) for this particular application can be related to the power available from Figure 5.3. [Tower, Astro, RBM, Aveox] Note that there is considerable scatter in the data for electric motor weights. This is probably due to the fact that some of the motors come from the factory with tachometers and gearboxes pre-installed. The lower bound for electric motor weights corresponds closely to that of the internal combustion engine weights, implying that an optimistic estimate would just be to use the internal combustion curve fit to estimate the electric motor weight.

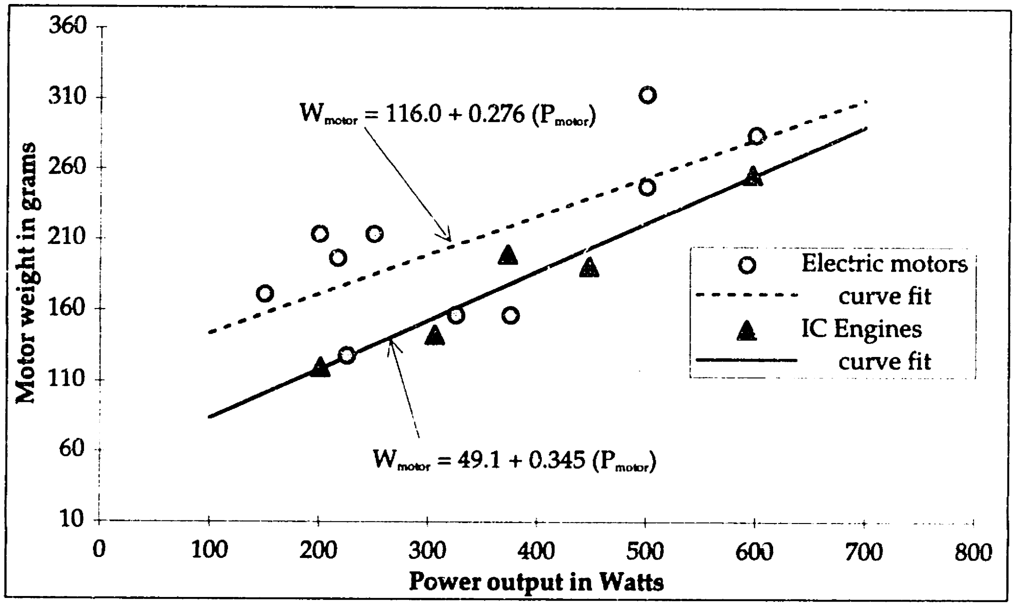


Figure 5.3. Weights and Power of Some R/C Model Aircraft Engines.

Since a typical tail-sitter configuration requires a thrust-to-weight ratio of about 1.4 for acceleration at takeoff [Covert], the motor sizing must take this into account as follows:

$$W_{motor} = W_o + \frac{\partial W}{\partial P} P_{motor} \tag{5.10}$$

$$P_{motor} = \sqrt{1.4^3} \cdot P_{req} = 1.6565 \cdot P_{req} \tag{5.11}$$

After performing a few sizing exercises, it was found that the linear fit for the electric motors was not very good at lower power outputs. A better approximation is shown in figure 5.4. These values for the slope and intercept should be used instead if the required power output is within range.

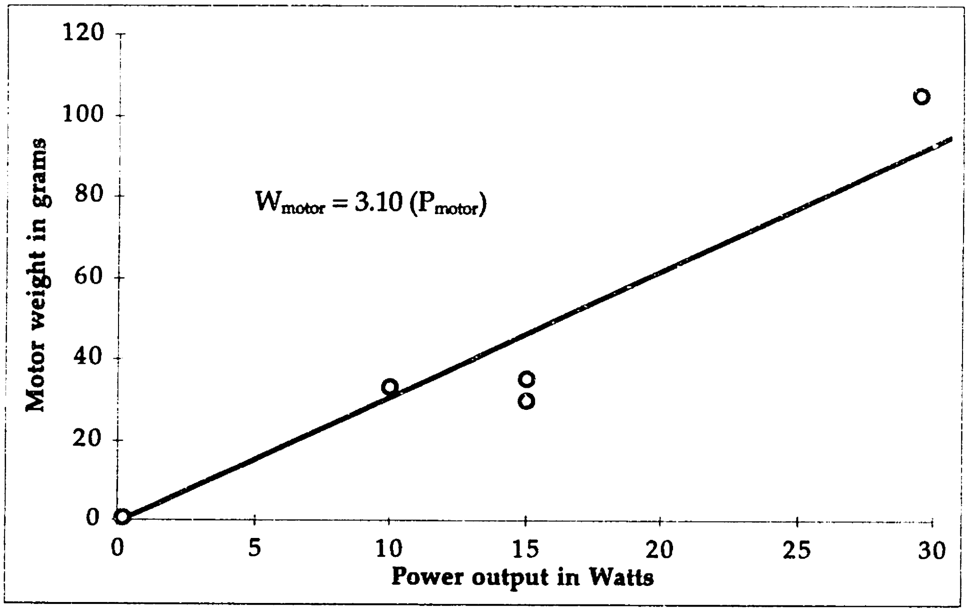


Figure 5.4. Weights and Power Outputs for Small Electric Motors [Namiki, Aveox]

To find $W_{batt\text{-}comms}$: A fraction of the total power budget will be used to provide communications capability for the S-UAV. This power requirement varies with the range, which varies over time. Assuming a constant cruise velocity (V_{fwd}) and a desired loiter time (E_{loiter}) at a given range (R),

$$W_{batt-com} = \frac{1}{\rho_p \eta_{alt}} \left\{ E_{loiter} P_{com}(R) + 2\int_0^{R/V_{fwd}} P_{com}(r(t))dt \right\} \tag{5.12}$$

where $r(t) = V_{fwd}t$ and ρ_p is the battery power density. Note that for a vehicle with no alternator (i.e. the internal combustion engine configuration) η_{alt} is equal to 1.0. For a micro gas turbine, a good estimate is to use a shaft alternator efficiency of 50%.

The power required to transmit data at a given range is shown in figure 5.5. The curve for non line-of-sight communications is representative of the power requirements for data transmissions within a somewhat cluttered urban environment. If only a simple line-of-sight communications capability is enough, much less power is used. It is up to the designer to determine which curve to use.

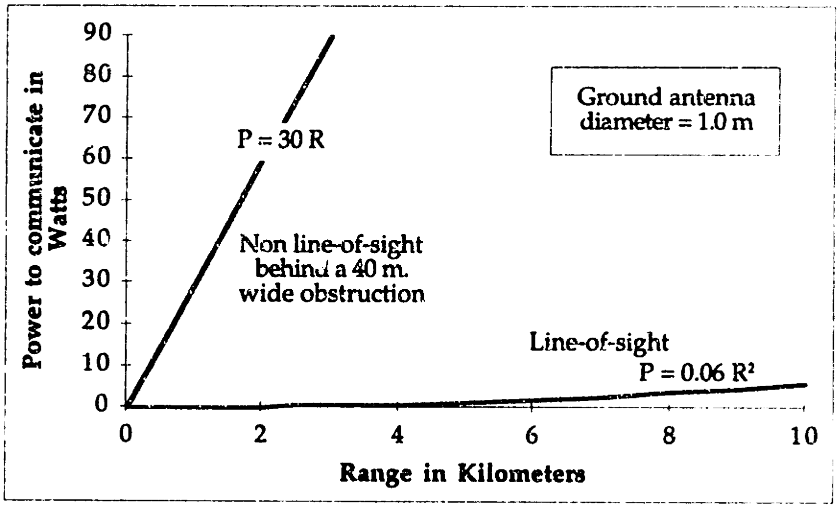


Figure 5.5. Power Required to Communicate to the S-UAV. [Gordon]

It was decided to design for the most critical case, that is, by accounting for the capability for non-line-of-sight communications. For reference, the battery weights needed for communications are given for both types of configurations:

$$W_{batt-comms} = \frac{30R}{\rho_p \eta_{alternator}}\left(E_{loiter} + \frac{R}{V_{fwd}}\right) \quad \text{(non line-of-sight)} \qquad (5.13)$$

$$W_{batt-comms} = \frac{0.06R^2}{\rho_p \eta_{alternator}}\left(E_{loiter} + \frac{2R}{3V_{fwd}}\right) \quad \text{(line-of-sight)} \qquad (5.14)$$

To find $W_{batt-systems}$: Another fraction of the total power budget will be used to power all the other electrical systems. The power requirements of these systems ($P_{systems}$) will be assumed to be constant throughout the entire mission:

$$W_{batt-systems} = \frac{P_{electrical}}{\rho_p \eta_{alternator}}\left(E_{loiter} + \frac{2R}{V_{fwd}}\right) \qquad (5.15)$$

The power consumption of the various systems is shown in table 5.1. It can be seen that various internal systems of a 1997 S-UAV configuration will have a combined power consumption ($P_{systems}$) of about 23.3 Watts. The micro gas turbine is not expected to be commercially available before the next decade. By the time it becomes available, it is safe to assume that the size and power consumption of the various systems will be reduced considerably. This is why two different values are given: one for the current 1997 technology, and one for the potential for the year 2007.

[illegible]	[illegible]		[illegible]	
	Weight (g)	Power (W)	Weight (g)	Power (W)
Antenna	10		10	
Camera	20	1.6	20	0.2
CPU(s) (486)	15	2.0	8	1.0
GPS	30	0.9	3	0.1
IMU	60	5.0	6	0.5
Interfaces (incl. diagnostics)	20		5	
Radio transmitter	60	1.8	6	1.0
Sonar ranger(s) (2)	50	0.5	10	0.5
Voltage regulators	5		1	
Total	**270**	**11.8**	**69**	**3.3**

Table 5.1. Current and Estimated Future Weights of Internal S-UAV Systems.

To find $W_{batt-motor}$: If the configuration is to be powered by an electric source, additional power must be budgeted to provide power for the electric motor throughout the entire mission:

$$W_{batt-motor} = \frac{1.2 \cdot P_{req}}{\rho_p \eta_{motor} \eta_{alternator}} \left(E_{loiter} + \frac{2R}{V_{fwd}} \right) \tag{5.16}$$

It is important to note that equation (5.16) is used in electric motor driven configurations only.

To find $W_{systems}$: The weight of the systems includes all the GNC, GPS, CPU, sonar and RF modem system components. This value is held constant, and its obtained from table 5.1.

$$W_{systems} = 270 \text{ g} \qquad \text{(1997 model)} \tag{5.17a}$$

$$W_{systems} = 69 \text{ g} \qquad \text{(2007 model)} \tag{5.17b}$$

To find W_{fuel}: The weight of the fuel needed to complete the mission is given by:

$$W_{fuel} = 1.2 c_p P_{req} \left(E_{loiter} + \frac{2R}{V_{cruise}} \right) \tag{5.18}$$

where the 1.2 factor is used to account for fuel reserves. specific fuel consumption (c_p) for R/C model engines is not found easily in the literature. It is typically not an important metric to hobbyists and manufacturers alike. A good estimate, based on typical engine running times and fuel tank volume, would be about a c_p of 2.0 g/W/hr. Note that (5.18) is used in internal-combustion engine configurations only.

5.3 Finding a Solution to the Weight Sizing Problem

Equation (5.9) can now be expressed as:

$$W_{total} = K_1 + K_2 P_{req} \tag{5.19}$$

where:

$$K_1 = K_{structure}\left(W_o + W_{batt-comms} + W_{batt-systems} + W_{systems}\right) \tag{5.20}$$

and K_2 is dependent on the power configuration:

$$K_2 = K_{structure}\left(1.6565\frac{\partial W}{\partial P} + 1.2c_p\left(E_{loiter} + \frac{2R}{V_{fwd}}\right)\right) \quad \text{(I.C. engine)} \tag{5.21a}$$

$$K_2 = K_{structure}\left(1.6565\frac{\partial W}{\partial P} + \frac{1.2}{\rho_p \eta_{motor}\eta_{alt}}\left(E_{loiter} + \frac{2R}{V_{cruise}}\right)\right) \quad \text{(electric)} \tag{5.21b}$$

This non-linear system of two equations and two unknowns can be solved numerically with methods such as Newton's, as illustrated in figure 5.6.

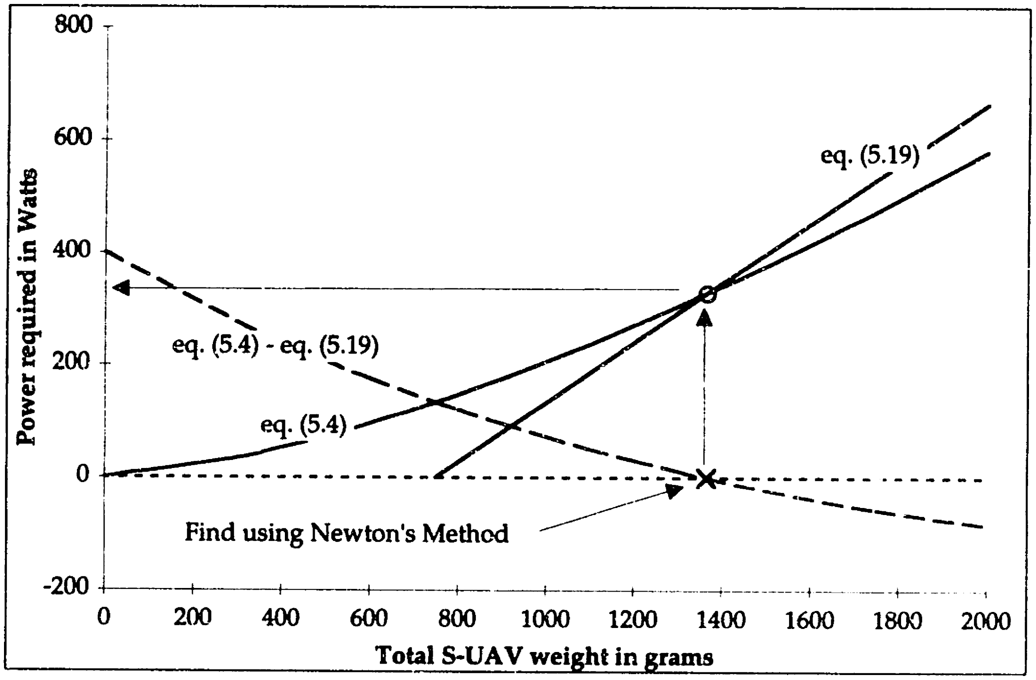


Figure 5.6. S-UAV Sizing Method Example.

Note that from figure 5.6, it is possible to either have either zero, one, or two different solutions. A simple check for the existence of a solution is to take the derivative of {eq. (5.16) - eq. (5.17)} and find the minimum. If a solution exists, then this minimum should be negative in value.

Chapter 6

Results of Parametric Studies

6.1 Justification for the Use of a Ducted Fan

Referring back to equation (5.2), it is evident that a large diffuser ratio (σ) is desirable in a hovering configuration. The proper method to increase this ratio is to enclose the rotor in a shroud. A properly designed duct can reduce the required momentum disk area by half, but it can also add considerable weight and complexity to the design. An excellent method to justify the use of a rotor duct is to trace the benefits back to the technical requirements derived in chapter 3, as illustrated in table 6.1. In this table, the "Rank" column is the weighing factor for each engineering characteristic. A "Rank" of "10" besides a technical requirement signifies that it is a critical one, which must be met at all costs. The other two columns describe the correlation of each configuration option with the technical requirements, as follows:

LEGEND	
9	Very synergistic
3	Somewhat helpful
1	Not very helpful
0	Not applicable

[illegible]	[illegible]	[illegible]	[illegible]
Collision avoidance system	10	1	9
Lightweight	9	9	1
Simple design	6	9	3
Few parts count	5	9	3
Small ground package	5	3	9
Efficient aero/propulsive design	5	3	9
Shielded sharp blades and heat sources	5	1	9
Strong structure	3	3	9
Excellent manufacturability	2	9	1
Quiet propulsion system	1	3	3
TOTAL PRODUCT		257	299

Table 6.1. Tracing the Need for a Ducted Fan to the Technical Requirements.

It is seen that a ducted fan, although potentially heavier than a simple rotor design, offers some considerable advantages over a free rotor. A duct would provide protection to the rotor blades from ingestion of foreign objects, and would reduce the likelihood of damage in case of a low speed collision. It would allow the vehicle to be a little smaller and it would shield the operator from high-RPM sharp rotor blades. A duct would also allows for a more robust structural layout, and it would provide a natural mounting location for most of the electronic equipment. As seen from table 6.1, ease of manufacturing is not a critical technical requirement, thus leaving no further objections to the use of a duct. All further calculations assume the use of a ducted fan configuration.

6.2 Parametric Plots

The equations listed in chapter 5 were solved and plotted against a set of desired mission ranges and maximum loiter endurance at range. Several different types of power system configurations were considered including an internal-combustion engine and electric propulsion (by lithium-polymer batteries). Additionally, electric propulsion generated by micro gas jet turbine engines coupled with shaft alternators was considered as well. All vehicles were sized assuming a capability for non-line of sight communications. This has the effect of increasing the battery weight many times over a line-of-sight-only configuration, but also making the design utility much more robust.

Figure 6.1 plots the solutions for various S-UAV's powered by an internal-combustion engine. The vehicle is capable of flying one kilometer out to an area of interest and then remain in loiter for a given endurance time, which is labeled by the various solid curves labeled "5 min", "30 min", and so forth. The various dashed curves represent the constant levels of power required (P_{req}) for flight. Figure 6.2 is a similar plot for a vehicle powered by lithium-polymer batteries at a nominal range of only 500 meters.

It is seen from both figures 6.1 and 6.2, that as the size of the fan gets smaller, the power required to hover and the total vehicle weight increases rapidly, up to the point of the minimum possible rotor diameter, no matter on how much power is available.

It is seen from figure 6.1 that a practical gas-powered S-UAV could weigh between about 1-2 kg and have a fan diameter of about 20-30 cm. This configuration fits in very well with the original design requirements outlined in chapters 3 and 4. On the other hand, a battery-powered S-UAV would be severely limited in its range and endurance capabilities, even when a substantially optimistic estimate for the power density is assumed, in this case: ρ_p = 300 W-hr/kg.

With respect to lithium-polymer batteries, the best 1997 technology can probably provide up to about 200 W-hr/kg, but not much more. There are also many other problems with using lithium polymer batteries as main power sources. The manufacturing process does not scale down very well to the battery sizes a S-UAV would need [Burnside]. These batteries are also very dangerous to operate, since they contain an equivalent explosive energy to TNT. Because of this, a large fraction of the total battery weight is tied up in the battery's protective casing. It is clearly evident that using lithium polymer batteries is simply not a viable way to power a small UAV system This will probably be the case for many years to come as well.

Another plot (figure 6.3) was constructed for a micro turbine powered S-UAV. The internal systems component weights were obtained from table 5.1. The major distinctive feature of this plot is that the weight of the vehicle has been reduced drastically. There is a very strong correlation between internal systems weight and total vehicle weight, thus a reduction in weight of about an order of magnitude is possible, depending on the weight of the internal electronics suite. The nominal rotor size seems to be about 12-18 cm, so there is about a 50% reduction in overall vehicle size as well.

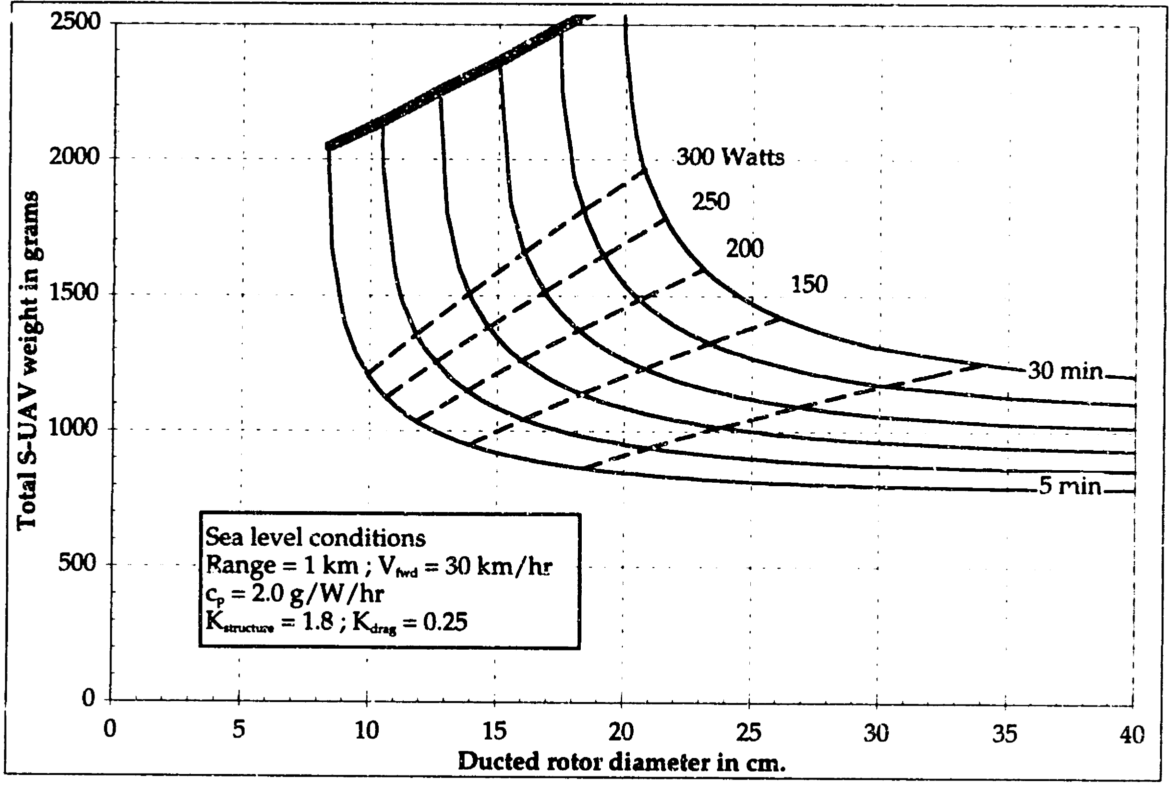


Figure 6.1. Possible Gas-Powered S-UAV Configurations.

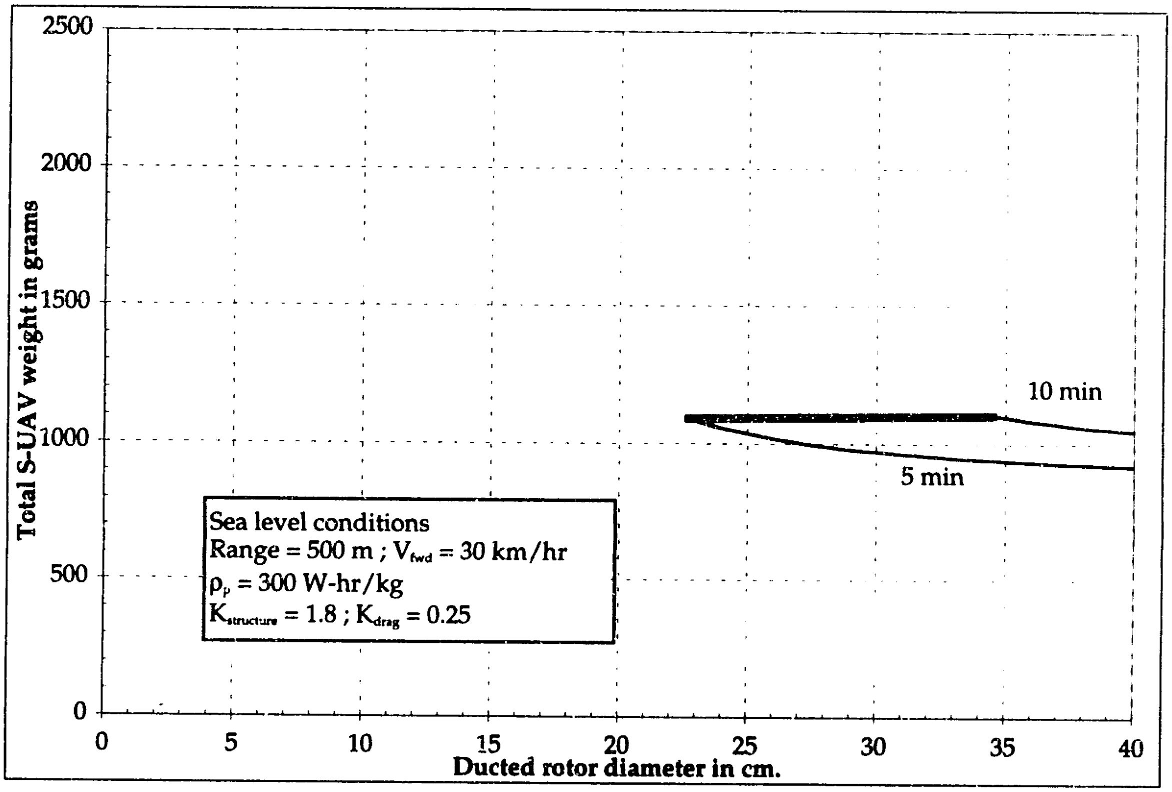


Figure 6.2. Possible Battery-Powered S-UAV Configurations.

The reduced mass of a turbine powered S-UAV is a major selling benefit, even more than the smaller size, because of the reduced kinetic and potential energy of the vehicle during flight. This translates directly into less potential for damage to the surroundings after a systems failure, reducing the liability concern of the civilian market. These results show much promise for the application of civilian S-UAV's in the future.

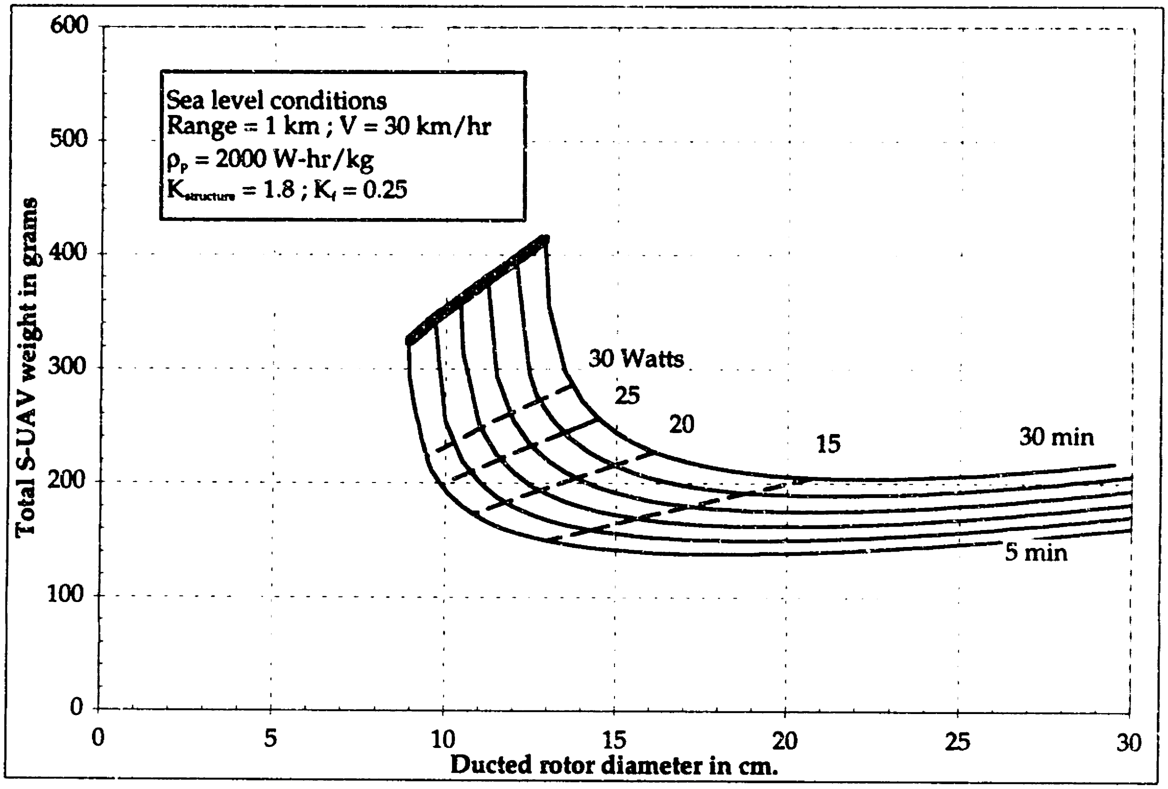


Figure 6.3. Possible Micro Gas Turbine-Powered S-UAV configurations.

6.3 Selecting the Design Points

The mission range and endurance is to be specified by the user and the intended application. From the market studies [Gordon] it was found that a suitable mission that would fit most markets was a 1 km fly out, loiter for 30 minutes and then return 1 km back to base. The ability to operate in all weather can be characterized by imposing a 30 km/hr forward flight capability requirement. This leaves the rotor diameter as the only remaining parameter to be chosen. It was found that by increasing the rotor diameter, the maximum range is increased (figure 6.4), assuming the power required (P_{req}) is kept constant.

From this point forward, all discussion will deal with the micro gas turbine S-UAV, since the gas powered UAV is covered by Gordon in his complimentary MEng thesis. Since both designs are practically identical in layout, and since the purpose of this study is to gain some insight into the potential sizes of S-UAV systems, this is considered adequate.

Micro gas turbine S-UAV sizing: A rotor diameter of 20 cm was chosen to continue the design process. This design point for the micro turbine S-UAV is shown in figure 6.5. Table 6.2 and figure 6.6 describe the most important characteristics of the micro gas-turbine powered S-UAV at this design point (20 cm).

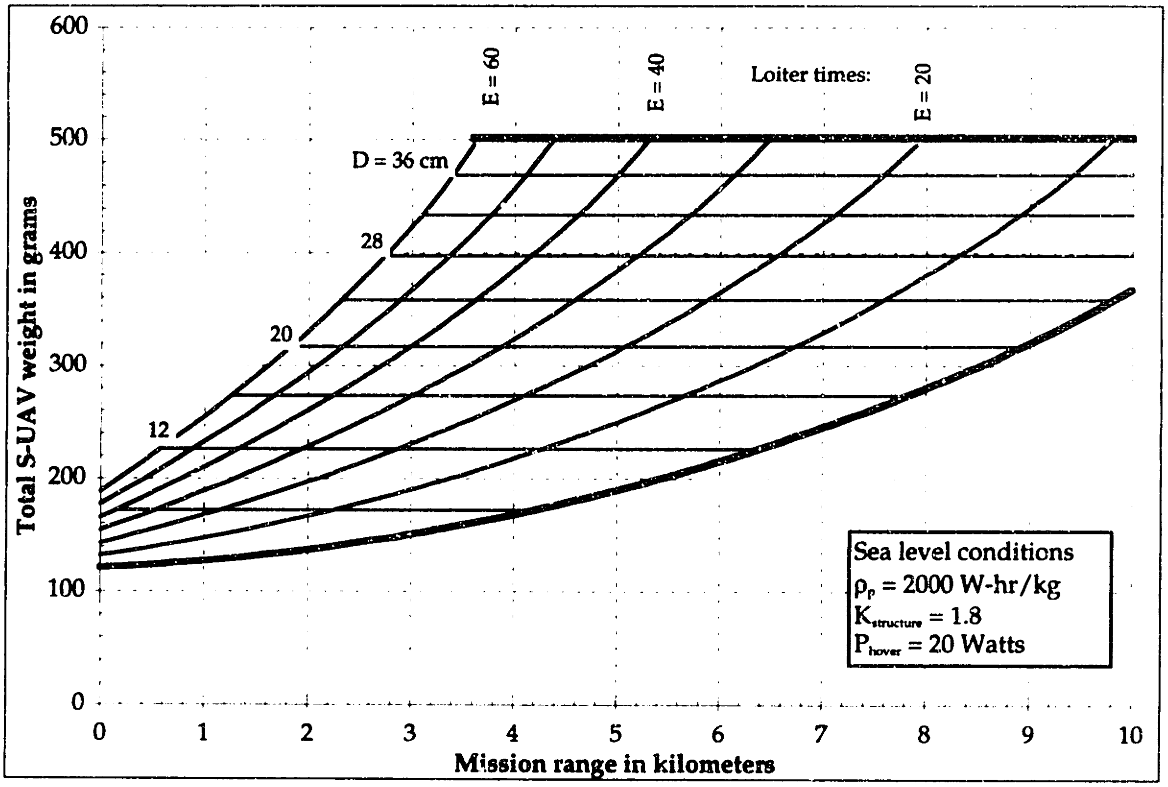


Figure 6.4. Gas-Turbine S-UAV's Powered by 20 Watts.

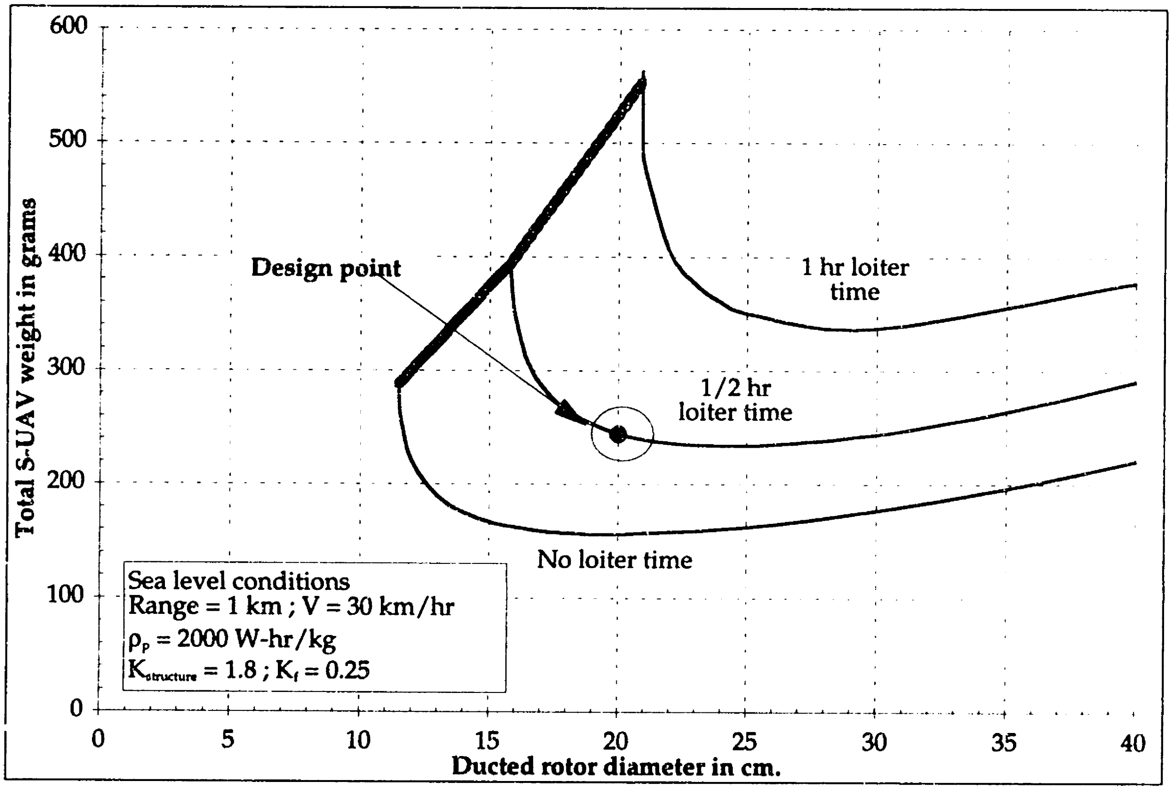


Figure 6.5. Choosing the Design Point for a S-UAV.

[illegible]		
Gas turbine fuel	26	g
Electric motor(s)	80	g
Electronics suite	54	g
Structural weight	128	g
TOTAL	**288**	g

[illegible]		
Comms (max)	143.7	W
Electronics	3.3	W
P_{motor}	25.7	W
TOTAL	**172.7**	**W**

[illegible]		
Tilt angle @ V_{fwd}	5.3	deg
Fuel volume req.	44.2	cm^3

Table 6.2. Characteristics of a S-UAV with a 20 cm Rotor Diameter.

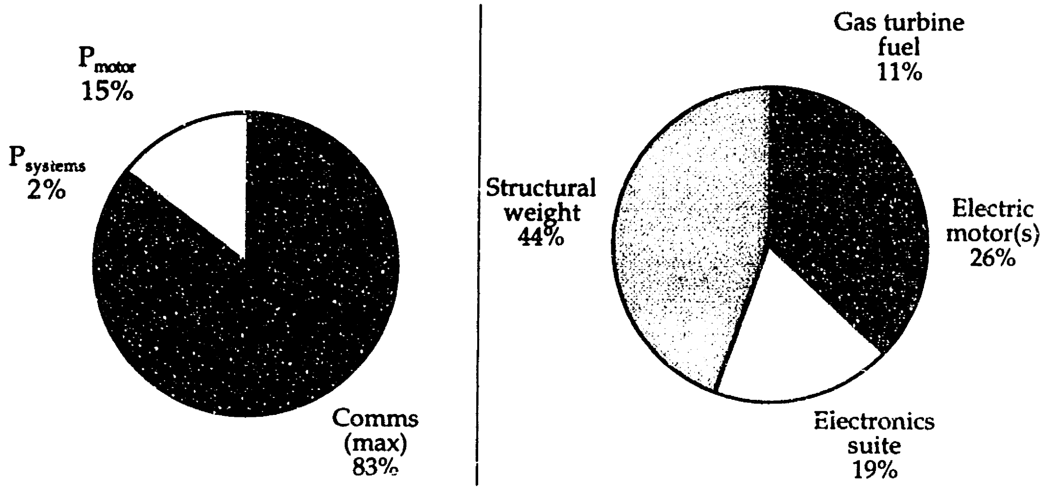


Figure 6.6. Power Budget and Weights for the Gas Turbine S-UAV.

Note that from figure 6.6, the power required to communicate at maximum range ($P_{comms-max}$) comprises 83% of the entire power budget. What this means is that maximum range is limited mostly by the ability to communicate more than any other factor. Another thing to note is the large proportion of the total weight the electric motors in comparison comprise, except for structure, and the surprisingly little amount of fuel needed.

6.4 Performance of the gas turbine S-UAV

A range-endurance polar is presented in figure 6.7, for both performance at sea level and at an altitude of 2500 m above sea level (standard atmosphere). As stated previously, the mission of this S-UAV is to fly out to range at a speed of 30 km/hr, loiter in a fixed location for a given amount of time, and then return back to base at 30 km/hr. The vehicle is designed to be capable of communicating with a 1 m diameter ground antenna behind obstacles up to 40 meters wide. Most of the power budget is reserved for communications.

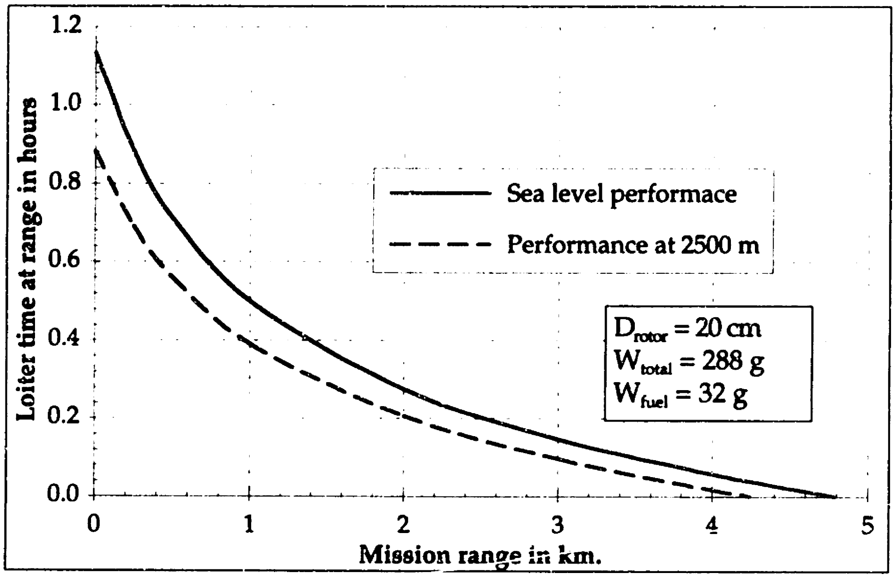


Figure 6.7. Performance of a Gas Turbine S-UAV.

Chapter 7

S-UAV Configuration Layout

7.1. Review of the Technical Requirements

The configuration of the S-UAV must be sensitive to the original technical requirements derived in chapter 3. The applicable requirements for this purpose are listed in table 7.1. The most critical issues are readily addressed by the use of a ducted fan configuration: a duct offers some degree of protection to the vehicle in case of a collision, it makes for an efficient aerodynamic design, and it protects the operator from the spinning rotors. If the micro gas turbines and the electric motors are enclosed in the duct, then these too are protected. It is also possible to use the duct as a heat sink, considering the large mass flow of air through it. Although a duct may add some weight, this may be offset by using the duct itself as the main structural element of the design. All electronics can be directly mounted on the duct, similarly with all other structure, such as motor mounts, fins, tails, or other aerodynamic surfaces.

It is also highly desirable to make the configuration aerodynamically stable, as this would reduce the complexity of the control system considerably. Another highly desirable feature is payload modularity, possibly some type of "plug and play" interface between video cameras, acoustic sensors, IR instruments, and chemical samplers. This would require separating integral electronics, such as the IMU, GPS, and the ultrasonic altimeters, from the mission specific electronics, such as cameras and probes.

If the S-UAV is to be operated at very close range (such as for inspection work), a tether can be used to transmit power and data to and from the vehicle, effectively providing it with virtually unlimited endurance and data throughput capability. A vehicle using electric motors is ideal for this type of setup.

One of the more surprising results from the QFD matrix is the very low priority on a quiet propulsion system. This indicated that a S-UAV can be loud if it has to be, for a civilian mission. This my not be the case for a purely military mission. It is not known to date how loud the micro gas turbines will be during operation.

	Structural Features	Operational Features
Critical	KE less than R/C glider Stable aerodynamic configuration Modular payload	Collision avoidance system Sonar altimetry Sonar navigation
Important	Use only proven designs Minimize parts counts Fuel efficient aero/propulsive design Authoritative control response Shielded sharp blades and heat sources Large power supply	GPS capable Tethered battery/comms system
Minor	Off the shelf components Hover-capable configuration Must withstand 40 km/hr impact Excellent manufacturability	Water resistant Non-flammable Inexpensive fuel/power source Exhausts must not contaminate data Must not be heard over 200ft Rechargeable power system

Table 7.1. Configuration Requirements for the S-UAV.

7.2 Configuration Options and Final Selection

For this study, three different types of possible S-UAV configurations were considered and analyzed: a Hiller flying platform, a freewing tilt body, and a ducted-fan tail-sitter, and each will be discussed briefly, listing both pros and cons to the design.

The Hiller Flying Platform: This configuration first made its appearance in 1955 as the Hiller ZV-1, as seen in figure 7.1. The main advantage to this design in an inherent aerodynamic stability, both statically and dynamically [Ando], which is a key technical requirement according to table 7.1. In order for the vehicle to meet this stability requirement, the center of gravity must be located about 1 rotor diameter above the rotor disk plane. Control of the vehicle is either achieved by lateral translation of the c.g., or by deflecting fins below the rotor, as seen in the UCF entry into the 1996 Aerial Robotics Competition [Sherman]. This inherent stability makes the design very attractive from a controls point of view.

The c.g. requirement (which is very counter-intuitive) for this vehicle is extremely sensitive and it also leads to a very bulky configuration. The platform is usually taller than it is wide, giving it the appearance of a fuel barrel, as seen in the conceptual S-UAV of figure 7.2.

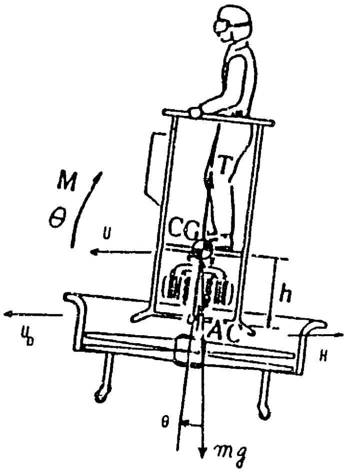


Figure 7.1. The Hiller Flying Platform. [Ando]

Another downside to the design is a severely limited forward speed capability. Preliminary calculations indicated a forward velocity of no more than 10-15 km/hr for a S-UAV of this size. This vehicle would be useless in ordinary windy days and would not provide the user "all weather capability" as required from the QFD analysis.

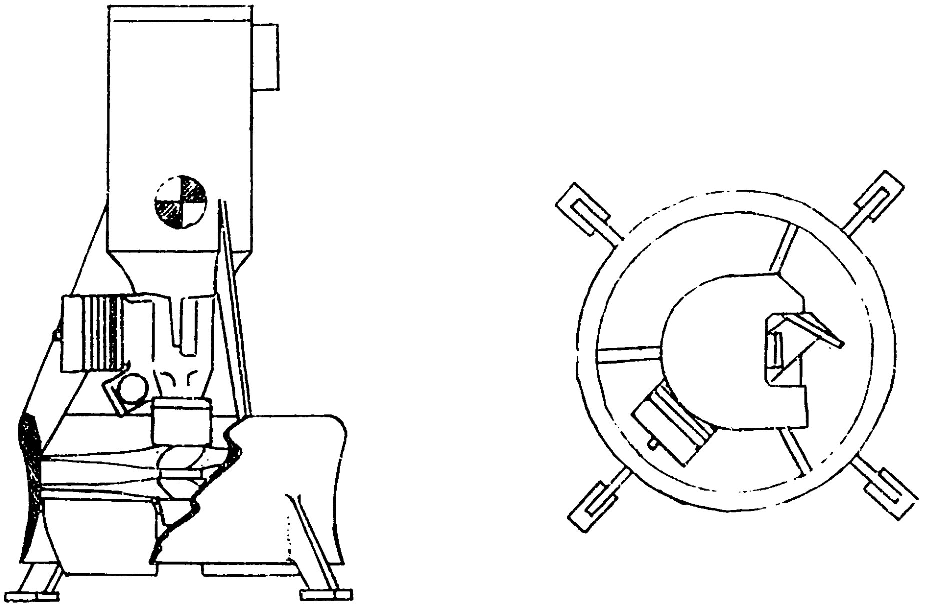


Figure 7.2. A Possible Hiller Platform S-UAV.

The Freewing Tilt-Body: The MATRA/Freewing Scorpion 50, has proven itself to be an extremely successful design for the role of a tactical UAV. Among its unique features are a stable transition from near-hover to high-speed cruise flight and a total insensitivity to c.g. location. Because of its gust-rejecting wing configuration, it is a very solid instrument mounting platform, even in the most turbulent and menacing flight conditions. With some modification to the propulsion layout and the tail moment arms, it is possible to achieve full hovering flight from the design, and thus be useful for the missions expected.

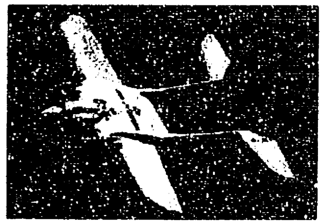


Figure 7.3. The Freewing Scorpion UAV.

This design could be a very good choice for a S-UAV, but a major drawback is the need to use wings in the configuration. This increases the size and weight of the vehicle considerably. Preliminary calculations show that for a 300 g vehicle powered by 26 watts, a wing area of about 400 cm^2 would be required to fly at a speed of about 56 km/hr. The wingspan of such a vehicle would be about half a meter.

The Ducted-Fan Tail-Sitter: This is a modification of the Hiller concept, in that the center of gravity is lowered, so that the vehicle is better proportioned, but at the expense of a more dynamically unstable configuration. This vehicle offers probably the most compact size of all, and it is reasonably fast (~30 km/hr) to be able to cope with gusty weather. But most importantly, this is a very simple aircraft to design, and it serves as an ideal first design iteration, although it may not be optimal. This was chosen as the final configuration for the S-UAV.

7.3 Propulsion Layout

For any hovering configuration a high disk solidity ratio is highly desired [Drela]. This must be traded off against increased losses at high forward speeds, though. Once the required disk area is found, it is possible to distribute this area between two or more separate disks, such as in a tandem twin-rotor configuration. This approach has some benefits, for example, the fans can rotate in opposite directions to counter the torque without using counter-rotating gearboxes. The disadvantages of using such a system is that the thrust to power ratio of the system decreases with decreased rotor size, and the blade RPM increases. For the sake of simplicity, a single fan is used to propel this S-UAV design.

The proposed configuration for the S-UAV features of two electric motors facing each other, each spinning a rotor in opposite directions. The distance between counter-rotating props should be in the order of one blade chord length. In order to keep a reasonable distance between the rotors, a blade chord to length ratio of 1/6 is appropriate.

The proposed configuration, using a 20 cm duct, will produce about 300 g of thrust with two electric motors, each rated at a maximum power output of 13 W each. The rotors will be spinning at 6200-6500 revolutions per minute.

The S-UAV will require about 147 W of power to be able to communicate at maximum range, and to be able to operate the sensors and control system. It will also need 26 W to be able to hover. Factoring into account a 50% alternator efficiency and a 70% electric motor efficiency, the total power budget is about 362 W. This translates into 30 to 40 micro gas turbine engines (figure 7.4), since each one is theoretically capable of producing 10-15 W of power. These engines are still in the early development phase. It is not yet known how these engines will be started.

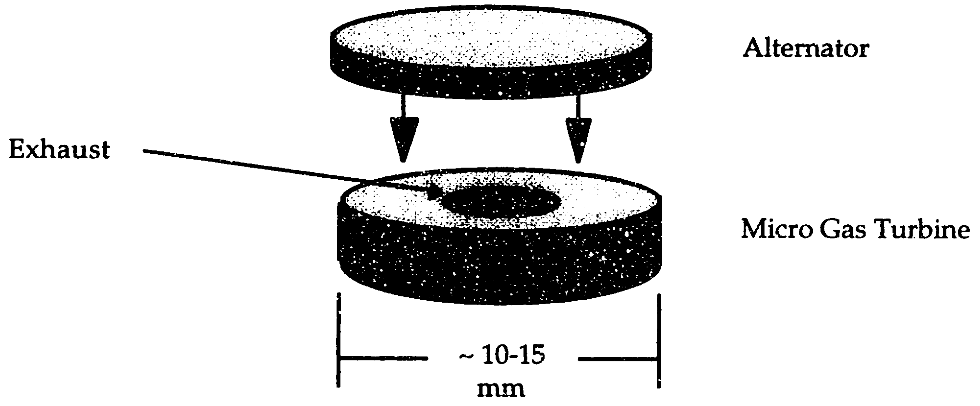


Figure 7.4 Basic Schematic of a Micro Gas Turbine Engine.

Chapter 8

S-UAV 3-View

8.1 Description of the Configuration

Since the configuration uses only a very small amount of fuel, it was found that all of it would fit inside a dorsal fin situated above the rotor duct (figure 8.1, "FUEL TANK"). This dorsal fin is also used to support the electric motor above the duct. This location for the fuel is very convenient, since it is above the gas turbine, allowing for a gravity feed without need for a fuel pump, and it is close to the center of gravity.

The micro gas turbines are situated on the inside surface of the duct, downstream of the rotor disk to assure adequate mass flow through the inlets (fig 8.1, "GAS TURBINES"). The turbines are coupled to shaft alternators producing electricity, which after going through voltage regulators, is fed to the two electric motors. Each motor ("ELECTRIC MOTOR") is typically about 1.5 cm in diameter and 3 cm long [MicroMo]. The motors are coupled to gearboxes to reduce the RPM and to increase the torque.

Since the configuration is unstable, a robust control system is required. The vehicle pitch angle is controlled by a pitch vane ("PITCH VANE") below the rotor. This vane is controlled by a electric stepper motor [Nakimi] so that no feedback loop is needed, it is hoped. Two other fins ("YAW VANE") provide bank if deflected together, and they provide yaw if deflected differentially. Further detail on the control system is described in the other MEng Thesis by Kim.

The IMU system for the S-UAV was originally intended to be used in an instrumented scalpel to be built by Draper Laboratories. It is small enough so that if fits inside a dorsal fin ("IMU") complementing the fuel tank. The GPS antenna is located over the top surface of the tail ("GPS ANTENNA"), where is can get an unobstructed view to the sky. There is also an ultrasonic sonar altimeter located in the tail section ("ALTIMETER"), and a second sonar up front ("SONAR") for collision avoidance.

The camera ("CAMERA") is mounted on a servo-driven swiveling system that allows it to pitch up-down and turn left-right. The entire front end of the vehicle is removable in case a different payload configuration is desired.

The horizontal surface is meant to shift the aerodynamic center of the vehicle aft, which should help provide some longitudinal stability during forward flight. The tips of the tail are canted downward in an inverted V-tail fashion to also provide some directional stability during forward flight. In addition, they serve as landing gear when the vehicle is on the ground. A simple wire is used as a nose gear ("LANDING GEAR WIRE"). This wire cross-section can be streamlined to reduce its drag, if needed

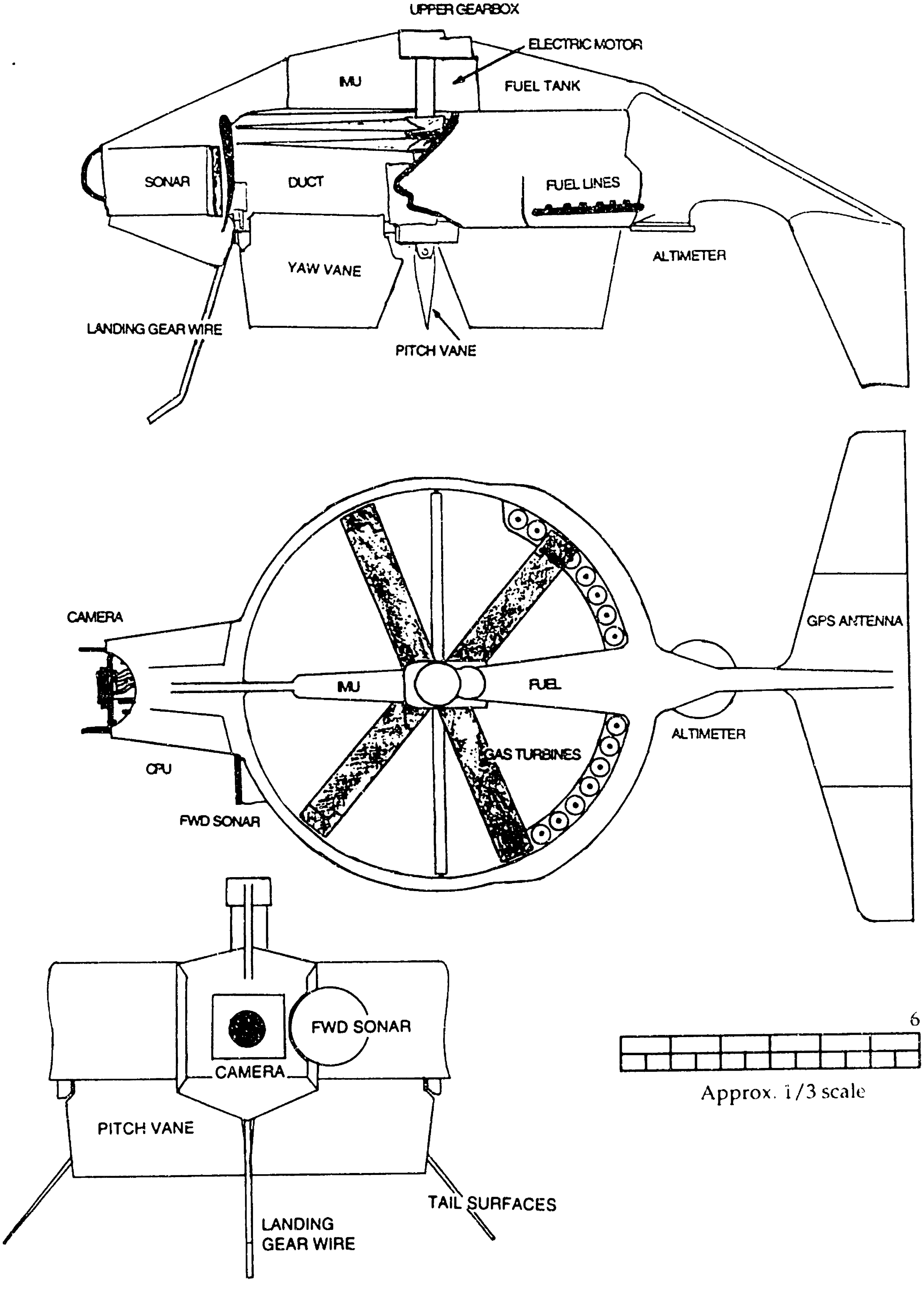


Figure 8.1. Preliminary S-UAV Design 3-View.

Conclusions and Recommendations

A preliminary design study of near-term and far term Small UAV (S-UAV) systems was performed by a team of MEng students in collaboration with MIT's Lincoln Laboratories. A possible list of missions for the vehicle was derived and a market field survey was performed to obtain real world potential customer feedback on the design idea. Some of the more feasible missions include: infrastructure inspection or news gathering, such as traffic reports. The customer needs obtained from field surveys were translated into technical requirements with the aid of a QFD matrix. This method showed some surprising results, for example, a very low priority on low noise emissions restrictions and covertness (for the civilian mission).

A major issue in entering the civilian market is accident liability. Small UAV systems offer a competitive advantage over larger systems which are to heavy and large to fly over populated urban areas safely. In terms of vehicle operation, fully autonomous flight may not be what is required, but maybe just simple "joystick" or "point and click" operation.

The major enabling technologies for S-UAV systems are:

- reduction of the internal sensor and GNC component weights
- obtaining a power source with very high energy and power densities

Since total weight and size is highly correlated to payload weight, miniaturization of the internal components should be a major focus. Substantial effort should go into developing lightweight electrical systems. Micro turbines show great promise for power generation for the future, but current-day technology can allow for a feasible (yet heavier) design using internal combustion engines.

The weight sizing method presented needs further refinement to confirm that the drag, weight and efficiency factors are adequate. Addition of other systems, like search lights for inspection, would require some minor modifications. It should be interesting to determine what size the line-of-sight-only configuration would be, and how much weight would be saved, since such a large portion of the total power budget is reserved for communications. Other configurations than the flying platform should be investigated, since the current choice was probably not optimal.

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