GEORGIA TECH

ELECTRIC PROPULSION INTEGRATION CONCEPT VEHICLE

(EPICV)

Final Technical Report on Phase I Research

Submitted to

Director, NASA Institute for Advanced Concepts (NIAC)

By the Georgia Tech Research Institute
Atlanta, Georgia 30332

28 May 1999

ACKNOWLEDGMENTS

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EXECUTIVE SUMMARY

The purpose of the TOROID ROTOR research was to explore the efficacy of toroid aerodynamic rotor with accompanying toroid rim drive motor applied in a new UAV system configuration. The role of the motor/rotor unit is to provide the propulsion for a high-altitude-long-endurance (HALE) UAV. The application encompasses systems technology, whereby the ultimate aircraft configuration would be sustained in flight with converted solar energy. Methods for obtaining the converted solar energy are investigated and presented as different modes of system design. Using aeromechanical analysis, it was determined that mechanical advantage {in the range of 30%-35%} is resultant from the rim drive method of driving the rotor. Also It was found, that since the configuration takes the form a ducted rotor, further benefit of approximately 15% may potentially be realized in propulsion system efficiency. Previous research was examined to determine where state-of –the-art in regen fuel cell technology and photovoltaic cells resides. The theoretical benefits of the toroid propulsion technology makes some power storage systems that heretofore were infeasible, now seem worthy of reconsideration.

Converted solar energy or advanced battery systems utilizing pulse-charging techniques may provide sustaining power. Solar energy conversion taking either of 2 modes—1) Photovoltaic conversion utilizing electrolyzer and closed loop fuel cells, or 2) From laser energy beamed from space borne platforms. In addition, with a different power storage concept such as advanced technology storage batteries with advanced pulse charging, there is an electric toroid UAV system that can perform many useful in-atmosphere missions. It would exploit the benefits of rapid pulse charge while out performing previous configurations of storage battery systems.

The findings indicate that there is a motor plan form that is significantly more energy efficient
than conventional electric motor designs with center-shaft plan form. A system using the technology described in this analysis would enable a commercially viable UAV capability that could be vertically launched from industrial facilities rather than airports that have long runways amenable to large aspect ratio fixed wing aircraft. In a commercial scenario, companies could launch the equivalent of a "surrogate communication satellite" from their onsite production facilities. The platform would climb to station altitude and be tracked via GPS while performing long duration mission such as communication relay—over major population centers, substituting for rocket launched communications satellites. This functional concept coupled with a technique of beaming laser energy from space borne platforms to HALE craft could dramatically decrease cost for wireless telecommunication service. This can be realized by harnessing a small segment of the space borne power conversion capability, which is intrinsic to the space borne missile defense system. Also the military has strong interest in developing "anti-aircraft immune" command & control platforms that loiter at high altitude for relatively long periods of time. The Marine Corps is especially interested in a system that can be launched vertically from a ship. A variant of the proposed system would be an ideal candidate for the capability being sought by DOD. Also there is potential benefit for enhancing the success of the existing long duration high fliers by adapting portions of the energy efficient toroid motor/rotor technology to the power/propulsion systems onboard these aircraft. In its ultimate configuration, the fully integrated system would enable industry to access the upper reaches of the atmosphere for commercial purposes—at less cost than rocket launched satellites.

The findings are consistent with the pillows of the NASA mission to develop useful technologies for commercial use of the air/space continuum. It supports the goal of novel and alternative forms of energy use while conveying and opportunity for a dual use of space borne missile defense technology that also benefits DOD as well. Potential utilization of space borne power derived from technology supporting missile defense is also consistent with NASA's mission as well. The novel concept of charging a fee for power consumption—which is ultimately applied to offset the cost of space born missile defense development, is a change in the paradigm of thinking about such matters that should seriously explored. For it is an example of how commercialization of access to space can benefit the public and private sector. If appropriate cost share arrangements are developed, it is likely that Congress would look upon such a program with favor.

SECTION 1

INTRODUCTION

This report presents the results of research in response to the NASA Institute for Advanced Concepts (NIAC) grand challenge in the area of Aeronautics and Space Transportation. The concept outlined here is for the development of an air vehicle with unlimited flight duration to be used as a communications relay platform and other observation missions within the atmosphere. By combining several emerging technologies, a revolutionary approach to telecommunications can be achieved within the next 10 to 20 years. The culmination of the proposed program will provide a technology base to industry from which a new generation of UAVs may be designed and employed.

1.1 Problem Statement

Explosive growth in the telecommunication industry has greatly increased the demand for satellite communication. The conventional approach to meeting this demand has been to launch more rockets with more satellites. However, this approach is very expensive. For example, launch operations require large teams of people, the small number of suitable launch sites can lead to scheduling conflicts, the rocket launch vehicle is discarded after a single use, failures in the rocket lead to the destruction of the entire system, guidance errors can place satellites in useless orbits, and satellite system failures are difficult (if not impossible) to repair.

Failures of the AT&T Telstar 401 on 13 January 1997 and the Panamsat Galaxy IV have amply demonstrated the vulnerability of telecommunication services to rocket launched satellite failure on 19 May 1998. In the case of the Galaxy IV failure, services to 90% of the 45 million to 50 million U.S. pagers was interrupted. Launch failures are costly as well. On 27 August 1998, a $225 million mission ended in catastrophe when a guidance failure in a Boeing Delta 3 rocket destroyed the Hughes Galaxy 10 communications satellite.

Other less obvious costs include the need for redundant systems onboard the satellite in case of failures and for hardening the satellite against damage from space junk. In fact, concern over space junk applies not only to communications satellites, but to manned space vehicles as well. In a recent news article (Ref. 1 Atlantic Monthly) it was noted that, “Each decade that it (the Space Station) is in orbit, according to a recent study, the station will have about a 20 percent chance of undergoing a ‘critical penetration’ that could kill a crew member or destroy the station – and the chances will increase as more objects are launched into space.” With another rocket launched into space every four days, on average, alternatives must be considered.

1.2 An Alternative Approach

Because of the high cost of rocket launched satellites, alternative approaches to providing transmission relay capability and expansion of bandwidth are being explored. Among these is the concept of using high altitude, long endurance (HALE) unmanned aircraft to carry telecommunication payloads (see Fig. 1.1). Such aircraft would fly station-keeping patterns over large metropolitan areas at altitudes between 60,000 ft and 70,000 ft (well above commercial airline traffic). This approach has the advantage of much lower launch costs. It offers a new operating scenario where a flight system could be launched with little more than a flight plan being filed with the FAA. Thus, the telecommunications industry gains control of the launch and tracking of their systems from their own facilities. Additional advantages are that the payload can be easily retrieved for repairs or upgrades and the air vehicle is reusable. For instance, communications payloads need not be designed with high levels of redundancy. Instead, in the event of a failure, a backup system could be kept on hand and flown in to position above any metropolitan area within hours. The failed system would be flown back for repairs then used as the new backup system.

The shortcomings to currently proposed designs include the need for large wing spans (200 ft or more) for efficient cruise, long runways for launching the aircraft, and a long term energy source. The Electric

Propulsion Integration Concept Vehicle (EPICV) was conceived on the basis of surmounting these shortcomings. First, the vehicle has a joined wing to reduce the overall span. Second, it has vertical flight capability, thus eliminating the need for long runways. Third, the propulsion system is designed to be electrical with power supplied from solar energy by day and from fuel cells at night. The main technology advancement to be demonstrated by the EPICV will be the systems integration and efficiency improvements required to enable 24-hr solar powered flight.

1.3 The Technical Challenges

The technical challenges facing the development of the EPICV can be grouped in two broad design areas: the aircraft configuration and the electrical power system. Aircraft configuration design covers the vehicle sizing for a specified payload, the general layout of the aerodynamic components, and the aerodynamic efficiency of the configuration in cruise. The electrical power system design covers the selection and integration of solar panels, fuel cells, electrolyzers, and batteries. The economic challenge to designing the EPICV will be the "cost to build" and the "cost of ownership", which include operations. If the EPICV approach cannot be shown to be a truly lower cost alternative to rocket launched satellites, it will not be a viable concept for this application regardless of it technical merits.

1.4 Summary

This report identifies and outlines the challenges in the critical technical areas. Extensive surveys were conducted to determine the capabilities of technology that is currently available and what may become available within the next 2-5 years. Also, detailed discussions are presented on the tradeoff studies that must be conducted before a feasible design can be achieved. These tradeoff and design studies, which must also factor in cost considerations, would constitute the second phase of research in systematic development of the EPICV.

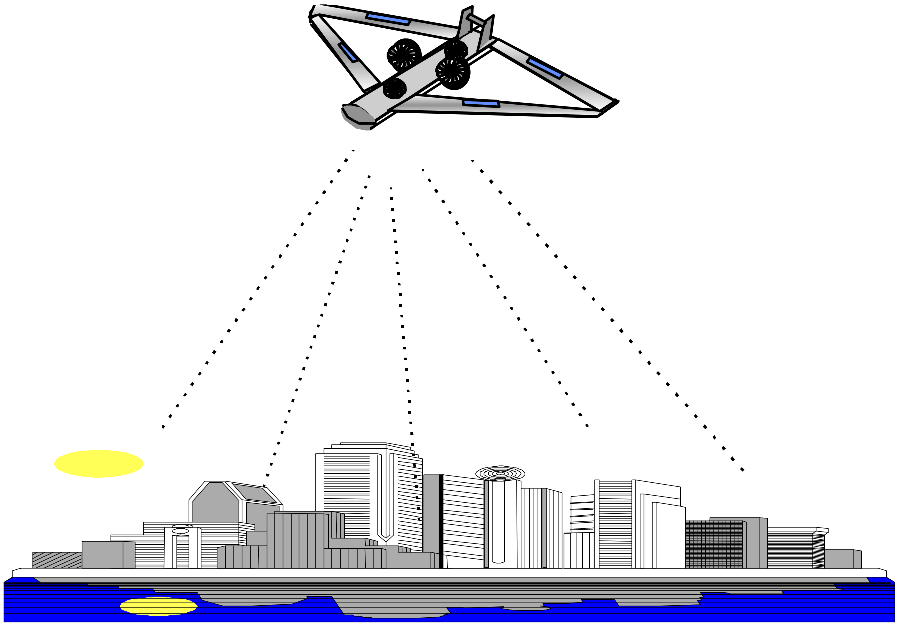

Figure 1.1 Alternative Telecommunications Relay Concept

SECTION 2

INTEGRATED SYSTEM CONCEPT

EPICV is a novel aircraft in many ways. It combines the characteristics of a vertical takeoff and landing (VTOL) aircraft with those of a high-altitude, long endurance aircraft. Its power system is a highly integrated set of components that manages the collection, storage, and conversion of solar energy for continuous 24 hour flight. Its design is driven by maximizing the overall system efficiency rather than by maximizing the efficiency of each individual component. EPICV also incorporates several new technologies in areas of electric motors, solar panels, and fuel cells.

2.1 General Overview

Figure 2.1 shows the general arrangement of the EPICV in a Joined Wing configuration for the HALE mission. The core of the vehicle is a VTOL platform with four ducted rotor units. The two larger lateral units can tilt 90 to give vertical thrust in hover and horizontal thrust in cruise. All four ducted rotors are based on a novel rim-driven electric motor/rotor unit referred to as the “toroid rotor.” For efficient cruise at high altitude, a set of high aspect ratio joined wings is attached to the core VTOL platform.

The wings and center body serve a dual function as solar power collection surfaces as their primary structure role. The upper surface of the vehicle is populated with photovoltaic (PV) cells. Their purpose is to convert solar energy into electrical power, some of which is stored by an electrolyzer while the rest is used directly by the dc motors. Three different power storage/supply concepts should be considered for sustaining flight. Within each concept the basic purpose remains the same—utilize some of the electrical power directly to drive toroid rotors for vehicle propulsion while the rest is stored for use at night.

The first power storage/supply configuration is a closed loop regenerative fuel cell system shown in Fig. 2.2. This is a system where the photovoltaic cells convert solar energy to electrical power, which is used by an electrolyzer to produce hydrogen and oxygen gas [Ref. 1]. The hydrogen and oxygen gases are fed to a regenerative fuel cell system that is designed as an integral part of the vehicle structure. The second power storage and supply concept is similar to the first except that the PV cells are laser energy sensitive whereby they convert beamed laser energy to electrical power—supporting regenerative fuel cell operation. The third system concept, is a battery storage system that is similar to the other two. In this case, the regenerative fuel cell with electrolyzer is replaced by a network of advanced chemical storage batteries with an advanced pulse charging algorithm. The electrical power from solar flux is converted to charging energy that replenishes the batteries via an advanced pulse charging device.

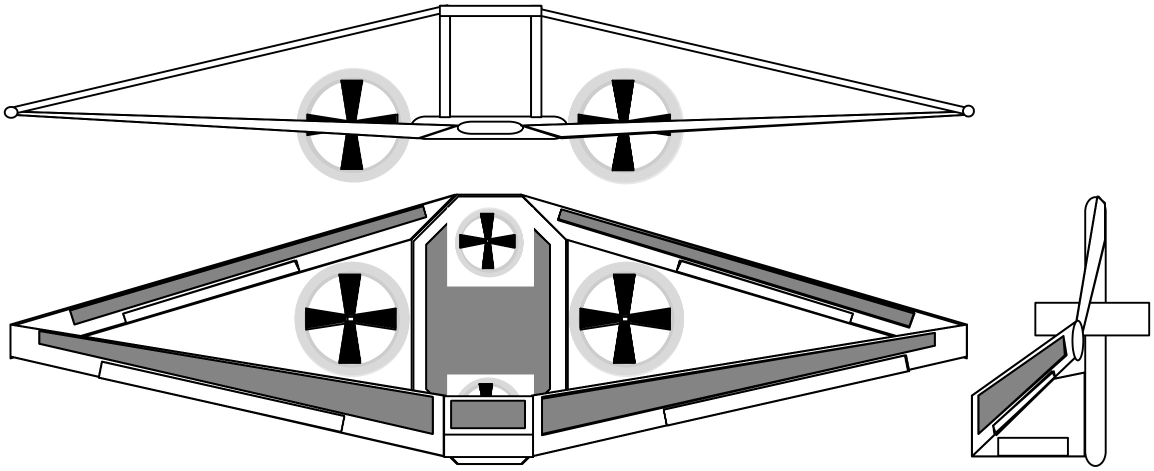

Figure 2.1 General Arrangement of the EPICV

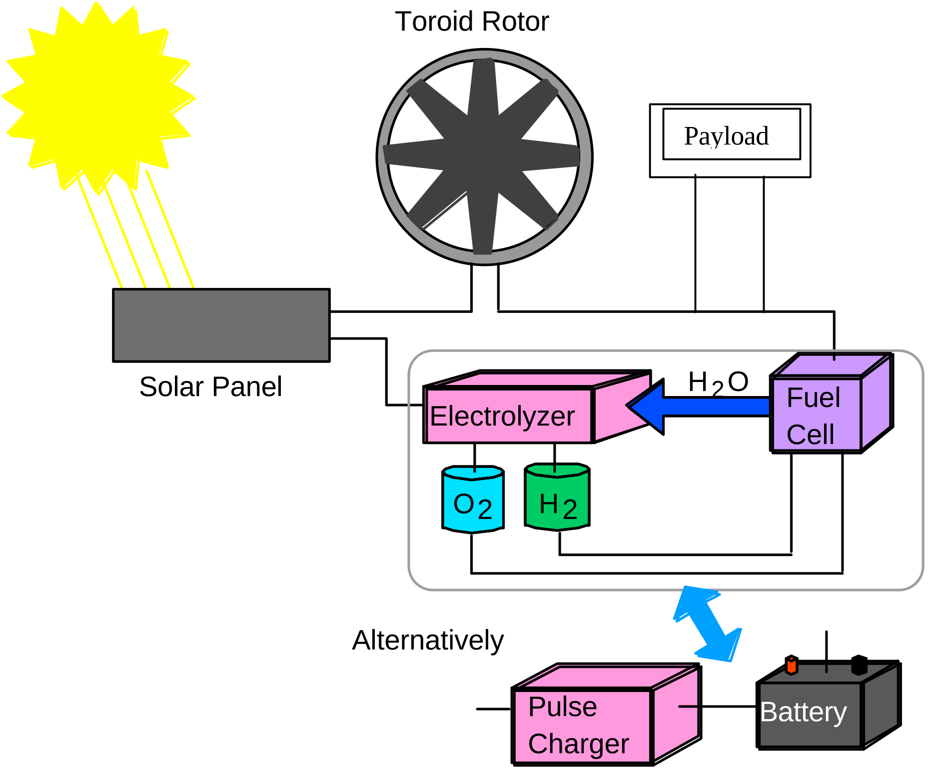

Figure 2.1 Power System Layout

2.2 Air Vehicle Configuration

This section gives a description of the important design features of the EPICV, including the joined wing configuration, toroid rotor, and electric power storage system. The integration of these features forms the foundation of the EPICV program.

2.2.1 Design Genesis

The EPICV was originally conceived as an electrically powered, VTOL unmanned aerial vehicle (UAV). Initially, the design concept was an aerodynamic lifting body and four rim driven motor-rotor units (MRU). The power system comprised a closed cycle arrangement of solar panels for energy collection, electrolysis for energy storage, and fuel cells for electrical power generation. To be capable of the HALE mission, however, the original EPICV design had to be melded with design aspects of other aircraft specifically designed for long range, long endurance, and high altitude. The key requirements for HALE and VTOL capabilities are typically met by two distinctly different aircraft types. High altitude, long endurance missions are usually the domain of fixed-wing aircraft, while VTOL missions are dominated by conventional helicopters.

A long endurance capability in any aircraft implies a minimum power design that is still able to meet the other design requirements. In the case of fixed-wing aircraft, minimum power is achieved by a high lift to drag ratio (L/D) usually associated with long, high aspect ratio wings and by large, low speed propellers (see Fig. 2.3) [Ref. 1]. In VTOL aircraft, minimum power is achieved with a large rotor system (low disk loading) and a minimal fuselage (low download) such as those found on conventional helicopters (see Fig. 2.4). The following discussion presents the advantages and disadvantages that these aircraft types have in meeting the overall HALE/VTOL mission.

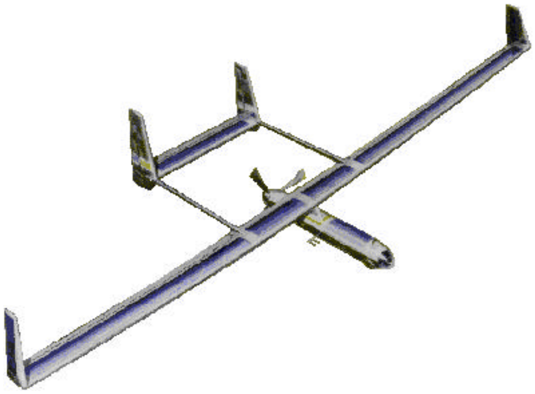

Figure 2.3 Notional High Aspect Ratio Aircraft for HALE Mission

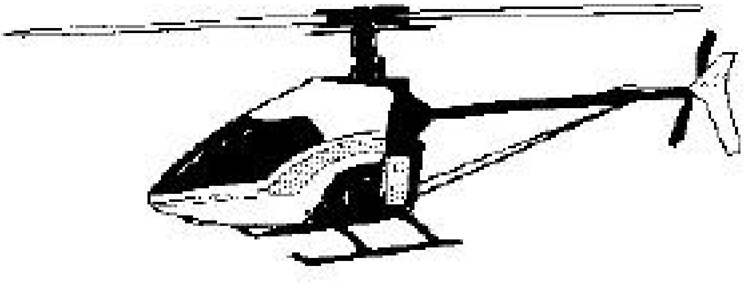

Figure 2.4 Conventional Helicopter Configuration

2.2.1.1 Configuration Comparisons

The high aspect ratio fixed-wing configuration has a significant advantage in terms of the lift to drag ratio. Ratios as high as 18 (ref. Roskam) are achievable at loiter speeds. The equivalent L/D for typical helicopters is on the order of 5 to 6 (Ref. Stepnewski and Prouty). Consequently, an aircraft with a high aspect ratio wing requires significantly less power than one relying on powered lift. The large wing also provides a significant surface area for the solar cells. Other advantages include the fact that a conventional design makes the performance analysis rather straightforward and it uses mechanically simple flight controls.

The main disadvantage to the high aspect ratio fixed-wing aircraft is that it is not VTOL capable and requires dedicated takeoff and landing sites. Also such aircraft are structurally fragile and susceptible to wing flutter. In addition, the large wing span makes ground handling difficult.

The main advantage conventional helicopters have is that they are VTOL capable. Their large open rotors represent the minimum power design for hovering. The narrow fuselage minimizes the download on the vehicle to improve hover efficiency. However, with respect to the HALE portion of the mission, conventional helicopters have several disadvantages. The low lift to drag ratio previously mentioned means they are not particularly efficient in cruise. Furthermore, their small fuselages present no significant surface area for mounting solar cells. The large diameter rotors that they require for efficient hovering cannot be shrouded in a practical manner and are, therefore, dangerous to ground personnel. They also require complex rotor hub mechanisms such as swashplates and pitch links for attitude control and auxiliary rotors for anti-torque and directional control.

2.2.1.2 Design Trades

Given the disadvantages inherent in each configuration, designers have come up with a number of alternatives for mitigating some of the shortcomings without creating a whole set of new ones. For example, one approach to overcoming the flutter problems of high aspect ratio wings is the joined wing concept (see Fig. 2.5).

Figure 2.5 Joined Wing Concept

Joined Wing: The joined wing concept offers several advantages that deserve further study. Wolkovitch, [Ref. 3] provides a summary of joined wing advantages:

- Light weight
- High stiffness
- Low induced drag
- Good transonic area distribution
- High trimmed $C_{l\ max}$
- Reduced wetted area – lower parasite drag
- Direct lift control
- Direct side force control
- Good stability and control

In Ref 3, Wolkovitch explains that, structurally, the joined wing provides a decisive advantage over conventional monoplane with tail design as far as weight of the final vehicle is concerned. A 24 % lighter aircraft may be realized employing the methods and techniques of joined wing design. The truss configuration of the fore wing, aft wing and fin provide a stiffer structure as much as 2.8 times greater than conventional wing-tail design. Buckling is not a major issue with normal loading applied to the rear wing. Wing torsion is also not a structural problem because the rear wing bending stiffness contributes to the front wing torsional stiffness.

In a discussion on fuselage weight, Wolkovitch cites two different references that show with a fixed fuselage length, tandem wing fuselage skin is lighter. This is because the two up loads from the joined wing impose less severe bending moment than the bending moment created by wing and tail loads of conventional design. Other factors also contribute to fuselage skin thickness but the joined wing configuration better reacts fuselage torsional and lateral bending; thus adding even further utility to the design concept.

The joined wing design also has an aerodynamic advantage. Using both wings to produce lift results in less induced drag than conventional wing design for equal lift and span while operating at the same dynamic pressure, according to Ref 3. However, the joined wing has a disadvantage in terms of parasite drag when compared to a conventional design. This results from a lower wing Reynolds Number (Re) and increased ratios of wetted area to lifting area due to dihedral cosine effect.

On the positive side, there are more benefits than disadvantages. The advantages are listed as follows:

1. Reduced wing area due to high trimmed C_{lmax}
1. Reduced fuselage wetted area due to reduced length
2. Improved wing fuselage interaction
3. Smooth fairing of landing gear
4. Fin-nacelle integration

The wing Re comparison shows that the joined wing has a lower Re than a conventional configuration, which could be as much as 40% lower according to Ref 3. This point does raise a possible consideration for laminar flow control since laminar flow control is easier at lower Re.

Air Foil Design: The joined wing being swept aft creates a flow where the boundary layer is swept back thus increasing C_{lmax} near the wing root according to Wolkovitch. He does point out that sharp nose airfoils are beneficial in that they may enable shed vortices, which will migrate outward along the wing leading edge increasing vorticity; thus increasing lift.

Control: The stall characteristics of the joined wing models and wind tunnel tests indicate the stall characteristics are good—no adverse attitudes such as "wings dipping" at stall have appeared. Adjusting positive or negative dihedral of front and rear wing can influence lateral stability of joined wing design. The spiral tendency of the joined wing design shows no tendency to dutch roll. Directional stability is good due to the effect of attaching the rear wing to the vertical fin. Control of the joined wing is versatile and can be easily achieved if each half of the wing is equipped with a control surface. Any desired control configuration can be achieved by coupling the individual control surfaces.

Ducted Rotors: For helicopters, some of the efficiency lost by reducing the rotor diameter can be regained by placing the rotor in a duct (see Fig. 2.6). This has the added advantage of making the vehicle safer for ground personnel. By imbedding the duct in the fuselage there is no download on the body. If multiple rotors are used, it is possible to balance torque without an auxiliary tail rotor; thus all the power goes into producing vertical thrust. It is also possible to control the aircraft without complex rotor hubs by using thrust variation on the different rotors. The drawbacks are that a ducted rotor will still not be as efficient as a much larger open rotor and the ducts produce drag in forward flight. Also, if the ducted rotors remain oriented vertically in forward flight they tend to suffer from pitch stability problems due to flow separation over the lip of the duct.

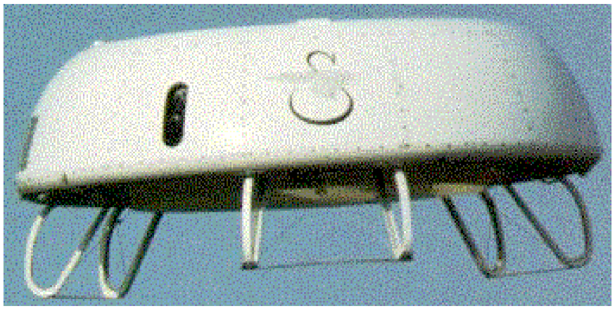

Figure 2.6 Ducted Rotor Air Vehicle (Sikorsky Cypher)

Tilting Rotors: A concept for improving the efficiency of rotorcraft in forward flight is tilting the rotor system such as is done on the tiltrotor (Fig. 2.7) and tilt-duct (Fig. 2.8) configurations. The advantage is that efficiency is greatly improved by maintaining the rotor system in axial flight. This also allows higher forward speeds and wing-borne lift. With wing lift, the power requirement for the rotor system is reduced, permitting the rotor to be turned at a slower speed. The disadvantage to this concept is, of course, the mechanical complexity involved in tilting the rotor system. There is also a weight penalty for the tilt mechanism.

Figure 2.7 Tiltrotor Aircraft (XV-15)

Figure 2.8 Tilt-Duct Aircraft (Doak VZ-4)

2.2.1.3 Applying the Design Trades to the EPICV

To perform the HALE/VTOL mission, the original VTOL design was modified to include some of the design features described in the previous discussion. Since vertical thrusters are not as efficient as wings for maintaining lift in forward flight, the goal is to transition the vehicle from thruster-borne flight to wing-borne flight as quickly as possible. Toward this end, the modified EPICV design includes a set of joined-wings (see Fig. 2.1). In addition, the two lateral MRUs are relocated outboard of the fuselage, greatly increased in diameter, and made tiltable. These MRUs will be the primary source for vertical lift and forward propulsion. The fore and aft MRUs were reduced in size slightly and are used primarily for pitch control in VTOL mode. As a secondary function, they can supply additional vertical thrust in hover and vertical climb. A horizontal stabilizer spanning the vertical tails was added to provide pitch stability and control and to reinforce the vertical tails to which the joined-wings are attached.

Mission flexibility for this unique type of air vehicle is preserved by making the large joined wings detachable. The remaining core vehicle, which contains all the avionics, payload, fuel cells, and propulsion system, will be capable of short range VTOL missions without the encumbrance of the large joined wings.

2.2.2 Toroid Rotor

The four ducted rotors (called toroid rotors) of the EPICV design are based on a mid-70s concept called the Electric Ring Propeller. Essentially, the outer rim of the rotor unit constitutes the magnet portion of an electric motor while the duct houses the coil portion of the motor (see Fig. 2.9). By driving from the perimeter of the rotor system, the motor is capable of delivering high torque. This concept has been made more efficient using a magnet flux management technique developed by Fisher Electric Motor Technology, Inc. The Harbor Branch Oceanographic Institute, Inc has used this technology to develop a solid-state underwater propulsion unit for battery powered vehicles (see Fig. 2.10).

(a) (b)

Figure 2.9 Toroid Rotor Components (a) Rotor, (b) Coil

Figure 2.10 Electric Ring Propeller

Applying the concept to an aerodynamic propulsion unit will require modifications to operate at higher rotor speeds and to achieve a much larger diameter. The lower density of air, as compared to water, drives the requirement for the higher rotor speeds. The larger diameter is required to reduce the installed power necessary for hovering flight. The primary modification, however, will be to reduce the motor weight to thrust ratio. In all aircraft designs, weight minimization is a key goal. The high efficiency of the toroid rotor concept will have to be fully exploited to minimize the propulsion unit's weight while maintaining a high power output. Another modification to the original underwater application will be in the blade design. Again, the difference in density between water and air will require the development of blades specifically designed to operate in air. The high altitude environment demands special air foil design. A trade-off must be achieved to come up with blade air foil design that can effectively operate at low altitude and by change in flow environment via rpm variation or mechanical reconfiguration via "smart structure" technology.

2.3 Power System

2.3.1 System Overview

For long duration loiter missions where solar energy will be used as the sustaining energy source, the upper surfaces of the vehicle will be used as mounting points for the photovoltaic cell arrays. In today's applications these cells are mounted directly to the upper surface and attached directly to the structural surfaces. For the contemplated system, an electrolyzer will use the converted solar energy to produce hydrogen and oxygen. Fuel cells dispersed throughout the vehicle structure receive the hydrogen and oxygen and convert it into electricity for the toroid motors.

2.3.2 Solar Cells

The three principal suppliers of space quality (lightweight) solar cells in the world are: SHARP, TECHSTAR and Spectrolab, a division of Hughes. Table 1 shows information gathered on the commercial specifications of currently available solar cells. Note that the weight per area is based on cell weight; thus, mounted module weight will be somewhat higher. Using the information from Pathfinder, as cited by reference [Ref 17] p5, the module fabrication adds 280 g./m^2 of weight and the cell packing density is only 90%. Note that calculations in Table 1 were made using AM0 sunlight of 1353 W/m^2 which is the sunlight spectral intensity in space. In addition, Table 1 calculations do not take into account operating temperature [Ref. 4]. Current NASA studies indicate that the power delivered from cells was often over-estimated because of temperature gradients of up to 10 degrees from the end of the wing to the center, thus causing reduced efficiency. Losses for silicon are on the order of 2.2 mV/^{o}C with a gain of 22 μA/cm^2. For multi-junction silicon and GaAs, these numbers are lower.

Using the table, a decision can be made about the primary design criteria: weight, area, and price. At this stage of analysis, the highest efficiency cells with the lowest weight will over-ride cost considerations for two reasons. First, because of the limited surface area on the air vehicle, efficiency per pound is paramount. Second, because of the fairly long lead time to the construction of a demonstration vehicle (two years or more), the cost per area is expected to come down for any given level of efficiency. This approach will at least permit the design of a functional system that will allow further investigation of the technical merit of the overall system. In this regard, future prospects for the 35-40% efficient cells from Spectrolab warrant tracking. However, the optimistic time frame appears to be more like 3-5 years since these are not yet working devices and Hughes has just started the development.

It is very apparent that the design criteria for terrestrial and space cells are optimized for different parameters. Weight is the primary area of concern for aerospace applications. Trying to use any of the lower cost terrestrial applications burdens the vehicle with specific energy requirements that defeat the utility of the design. However, lack of need for radiation protection is a primary difference between the design criteria for space applications and high altitude vehicles. There appears to be at least one technology, multilayer thin film polycrystalline silicon, that is of fairly high efficiency, with the promise of low cost. It is not likely to be useful for space applications because of the lower radiation protection, and it has therefore been developed for terrestrial applications, with little concern over weight issues. If the potential market for high-altitude-in-atmosphere aircraft is sufficient, research into lightweight, non-space quality cells, such as described herein, and may warrant research on the thin film cells for HALE application.

As part of the preliminary research into solar cell technology, several nationally recognized experts in the field were consulted. Among these was Mr. Dennis Flood from NASA Power Systems, Lewis Research Center. The following are some of the insights Mr. Flood had to offer:

> The Ames Research/Aerovironment team is using silicon (Si) or gallium arsenide (GaAs) space solar cells. In the near term, this is all that is available. In the last 4 years, the space market has shifted from using 10% GaAs to using 90% GaAs, with the balance being silicon. U.S. suppliers have effectively stopped making Si space cells. It appears as if U.S. suppliers have stopped innovating on space silicon, and though they may still supply it, it is not the best performance available. The best Si cells are from SHARP Corporation in Japan, and they dominate any sales of space silicon. There is basically no supply in Europe right now. They stuck with the older Si technology, and are now 10 years behind in development of GaAs technologies.
>
> The estimated costs for commercial space solar cells are as follows. The best Si cells (SHARP) are about \$100/W. GaAs cells are \$200-\$300/W depending on customer qualifications and quantity ordered. Multi-band gap cells with 22%+ efficiency are \$400-\$1000/W. China is increasingly producing the older, space station 14% efficient Si cells for ~\$100/W, but in large area (8x8) which saves on module assembly costs.

Based on this information, a typical array will cost \$1500-2000/W including at least \$1000/W to mount the cells on the surface of the vehicle. Using lower grade labor (i.e., graduate students) for assembly can reduce this cost.

From another subject matter expert, Mr. Dave Bents of the NASA Glenn Research Center (formerly Lewis), it was learned that the Martian atmosphere is similar to Earth's at 100,000-ft altitude. Consequently, the attributes of a HALE UAV may have application in UAV design for exploration of Mars.

Several emerging developments in solar cell technology may be applicable to a commercially viable EPICV. An ideal application would be a monolithic integrated thin film solar blanket. This has been pictured in a mock up for a lunar landing where the cells are on a flexible blanket that can be erected like a tent and provide power and shielding. The most mature thin film technology producer is Iowa Thin Films. They have an amorphous cell on Kapton with about 5% efficiency. The contacts are screen-printed silver paste, which is not space qualified, but it might hold up at 100,000 feet. They used a roll process with 14 inches wide by 1000 ft cells. Any combination of voltage, current, and size can be made.

Unisolar can make 8-10% efficiency cells on a silicon substrate. This is lightweight compared to glass and can be etched to .5 mil thickness for further weight savings. They have done this for some 1 ft x 1 ft cells for use on the space station, but not in larger areas. Cost for this technology is unknown.

Finally, Global Solar in Arizona is attempting to make $CuInGaSe_2$ (CIGS) on titanium foil or a polyamide substrate. Their process is not yet reliable, but the goal is to produce rollable cells 10% efficient (in space conditions) at 14 inches by 1000 ft.

2.3.3 Fuel Cell /Electrolyzer.

Significant research is currently being conducted in fuel cell and electrolyzer development, with several approaches are being taken in their application. Stand alone or distinct fuel cell functions by combining hydrogen and oxygen to generate electrical power, water, and waste heat. An electrolyzer generates hydrogen and oxygen from the dissociation of water using a dc electric current. Some fuel cell designs can be operated in reverse process and, thereby, serve a dual role as an electrolyzer. Such dual mode devices are referred to as unitized fuel cells. An integrated system of a fuel cell, electrolyzer, gas storage containers, and solar panels is known as a regenerative fuel cell.

Of the five main types of fuel cells, NASA has long used ones using alkaline potassium hydroxide as the electrolyte on space missions. These cells can achieve power-generating efficiencies of up to 70%, although they have been too costly for commercial applications. Fuel cells with a proton exchange membrane (PEM) as the electrolyte are another type that operate at relatively low temperatures (~ 200 F) and have a high power density. The U.S. Department of Energy considers the PEM fuel cell to be the primary candidate for light-duty vehicles and potentially for much smaller applications.

NASA has been working in fuel cell development with Proton Energy for unitized regenerative space fuel cell systems and with Lynntech for distinct cells. Both of these projects are sponsored by SBIR grants. Aerovironment and Dreiden Center are also developing fuel cell technology. At present, no working lightweight regenerative fuel cells exist, but Proton Energy's web site does list 400 Wh/kg as a current power density for a PEM type fuel cell. Given this level of power density, it may be worth considering this fuel cell for application in a closed loop system demonstration.

In addition to their unitized fuel cell developments, Proton Energy Systems supplies commercial electrolyzers. They have already supplied an electrolyzer to NASA Lewis for some testing of gas handling systems. Proton Energy Systems' electrolyzer is also based on the PEM technique. One design advantage of PEM electrolyzers is that they put out pressurized hydrogen (easily 400 psi), so no compression equipment is necessary. The hydrogen is stored in pressurized composite tanks. It is not known what design considerations are being used for oxygen storage/compression, or if the plan is to use atmospheric oxygen. Lack of oxygen at high altitude would lead to a consideration of some type of storage tank.

Unitized fuel cells are attractive from a design efficiency view in that a single device can be used to perform two functions. However, design considerations for a unitized fuel cell include matching the voltage requirements for its two roles. The fuel cell operating voltage is 1/2 the voltage of the electrolyzer operating voltage for a given cell. The difference must be compensated for through power conditioning. Another problem is one that Proton is having with its unitized fuel cell. The carbon paper used in the Membrane Electrode Assembly (MEA) is degrading when the stack operates as a fuel cell. In other words, it has not been as simple as just feeding gases through a standard or custom electrolyzer to generate electricity.

A phase II SBIR contract for a design of a lightweight electrolyzer/fuel cell combination using discrete cells for each rather than unitized cells will commence in the very near future. With the level of activity ongoing it appears that progress is being made in the fuel cell development area. This leads to the projection that the fuel cell technology will be ready to support the development of a vehicle such as EPICV in the next 3 to 5 years.

2.3.4 Battery Storage/Rapid Recharge

An alternative to a fuel cell/electrolyzer combination for power storage is a battery/recharger system. Recent research at Georgia Tech has produced advanced battery charging technology that has potential application to UAV systems. An advanced pulse-charging algorithm has been demonstrated on nickel metal hydride (NMH) and lead acid (LA) batteries. The premise of the advanced pulse charge is quite simple. By structuring a charge waveform (input energy) that is correlated with the state-of-charge (SOC) of the battery a highly efficient charge process can be accomplished. The batteries can be charged back to 100% SOC without the hazard of "thermal runaway" (i.e., melting the battery down). The cycle life for the battery is enhanced due to the lack of heat stress which decreases cycle life and the over-charge and under-charge phenomenon which also can influence cycle life. A further dimension to the advanced battery charging technology is the battery management system (BMS). The BMS is necessary to properly manage the charge process as well as to provide network control over the battery banks that function on a load share basis.

The battery storage system while having a lower power density than a regenerative fuel cell system or a beamed energy conversion system does offer some benefit over conventional design approaches. Aircraft that are battery powered (with rechargeable capability) could fly for relatively long periods of time based upon cycle life of the batteries. With proper BMS management of the charge process and temperature control, battery cycle life will be near the maximum design capability. Typically this could be 800 to 1, 000 cycles for a 32 amp-hour battery.

High-power electronics will not be required to manage the waveform for recharging. The proper waveform can be implemented in low power circuits and signal conditioned. Separate circuits then boost the strength of the charge pulse to the required levels. Since the BMS controller would be designed so that each battery is charged individually, high voltages associated with pack charging are avoided. Therefore, electrical power from PV cells with some power conditioning is capable of charging battery packs supporting the electrical propulsion system. It should be noted that because of its lower power density, toroid rotor with its minimum electrical power consumption becomes an attractive performer. Further analytical work is needed to sharpen the perspective on whether an advantage may be found in using battery storage in conjunction with a toroid motor/rotor configuration.

Comercial Solar Cell Specifications

Manufacturer		Product	Type	Efficiency	Weight mg/cm^2	Price per cm^2 (note 1)	Thickness(μ m)	Watts/m^2 at AM0 (note 2)	Watts/kg	Price/m^2	Price/W
Techstar	1		Silicon	12.5%	55	$1.50	200	169	308	$15,000.00	$88.69
Techstar	2		Silicon BSFR	14.7%	55	$1.96	200	199	362	$19,600.00	$98.55
Techstar	3		GaAs-Inventory	17.5%	93	$6.50	140	237	255	$65,000.00	$274.52
Techstar	4		GaAs	19.0%	93	$8.00	140	257	276	$80,000.00	$311.20
Techstar	5		MultiJunction	23.0%	93	$9.00	140	311	335	$90,000.00	$289.21
Spectrolab	6	K4702	Siilicon	13.3%	55		200	180	327		
Spectrolab	7	K4710	Silicon	12.3%	55		200	166	303		
Spectrolab	8	K6700B	Silicon	13.7%	24		62	185	772		
Spectrolab	9		GaAs/Ge-Single Junction	19.0%	100		175	257	257		
Spectrolab	10		GaAs/Ge-Single Junction	19.0%	80		140	257	321		
Spectrolab	11		GaInP2/GaAs/Ge-Dual Junction	21.5%	100		175	291	291		
Spectrolab	12		GaInP2/GaAs/Ge-Dual Junction	21.5%	80		140	291	364		
Spectrolab	13		GaInP2/GaAs/Ge-Triple Junction	24.0%	80	$10.07	140	325	406	$100,663.20	$310.00
Spectrolab	14		GaInP2/GaAs/Ge-Triple Junction	26.0%	80	$10.91	140	352	440	$109,051.80	$310.00
Spectrolab (note 3)	15	DEVELOPMENT	GaInP2/GaAs/Ge-Triple Junction	26.0%	58		102	352	607		
Spectrolab (note 4)	16	DEVELOPMENT	Four Junction Cells	35.0%	100			474	473.55		
SHARP	17	Light weight	Silicon	17.0%	17			230	1353		

Sample requirements for 14800 Watts of Power

Enter Power Requirements (watts) 14800

Manufacturer		Weight (kg) for 14800 Watts/kg	Area (m2) for 14800 Watts	Price ($) for 14800 Watts
Techstar	1	48.1300813	87.50923873	$1,312,639
Techstar	2	40.92693988	74.41261797	$1,458,487
Techstar	3	58.13113716	62.50659909	$4,062,929
Techstar	4	53.54183685	57.57186758	$4,605,749
Techstar	5	44.23021305	47.55936887	$4,280,343
Spectrolab	6	45.23503882	82.24552512	
Spectrolab	7	48.91268425	88.93215318	
Spectrolab	8	19.16260702	79.84419592	
Spectrolab	9	57.57186758	57.57186758	
Spectrolab	10	46.05749407	57.57186758	
Spectrolab	11	50.87746438	50.87746438	
Spectrolab	12	40.7019715	50.87746438	
Spectrolab	13	36.4621828	45.5777285	$4,588,000
Spectrolab	14	33.65739951	42.07174939	$4,588,000
Spectrolab	15	24.40161465	42.07174939	
Spectrolab	16	31.25329955	31.25329955	
SHARP	17	10.93865484	64.34502848	

Module Estimate Data (note 5)

Manufacturer		Weight of circuits, laminant, etc.(kg/m2) (note 5)	Area (m2) for 14800 Watts at 90% Packing Density
Techstar	1	0.28	97.23249
Techstar	2	0.28	82.68069
Techstar	3	0.28	69.45178
Techstar	4	0.28	63.96874
Techstar	5	0.28	52.84374
Spectrolab	6	0.28	91.38392
Spectrolab	7	0.28	98.8135
Spectrolab	8	0.28	88.71577
Spectrolab	9	0.28	63.96874
Spectrolab	10	0.28	63.96874
Spectrolab	11	0.28	56.53052
Spectrolab	12	0.28	56.53052
Spectrolab	13	0.28	50.64192
Spectrolab	14	0.28	46.74639
Spectrolab	15	0.28	46.74639
Spectrolab	16	0.28	34.72589
SHARP	17	0.28	71.49448

NOTES

1) Price Data are working estimates not price quotes
2) Calculations based on cells only at AMO sunlight (1.353 kW/m^2)
3) 102 μ m (4 mil) cells may be possible
4) 35% Cells have not been demonstrated as a working device
5) Packing Density and Module weight are from reference [13]

Table 1.

SECTION 3
TECHNICAL CHALLENGES

All of the challenges that are normally faced in a new conceptual design are present for the EPICV. To scope the problem down to manageable size, three aspects of this technical challenge were identified. The three key aspects of the technical challenge are:

1. Balancing power required against power available
2. Designing for a sufficient payload margin
3. Obtaining the maximum aeromechanical efficiency

3.1 Power Required/Power Available

The power required to raise an aerial vehicle to 70k-ft altitude can be broken down into segments. The first segment is the takeoff. In this segment, the vehicle is accelerated forward until a sufficient airspeed is reached that will sustain wing borne flight. Next the climb segment occurs. Power necessary to sustain the vehicle's forward speed plus the power to climb is required in this phase. In addition to the power to overcome gravity for take off and climb, there must be sufficient power to overcome drag. Induced, parasite, and skin friction drag are the components of power requirement where certain design characteristics are more efficient than others. Of course, in any vehicle design tradeoff, efficiency is sought within the parameters of the mission scenario. For takeoff and climb the considerations are straightforward—minimize power required for these phases of flight minimize weight and also to conserve power for other aspects of mission performance.

3.1.1 Takeoff and Climb Power

For takeoff and climb power required, the EPICV flight parameters for weight and drag appear to be most efficiently addressed with a joined wing design. In this research it was found that the joined wing design concept specifically offers an advantage over conventional monoplane and tail design for weight, induced drag, and skin friction drag. Reference 3, specifically addressed these areas and reports the advantages of the joined wing design over a conventional configuration.

3.1.2 Cruise Power

In the cruise phase of flight, induced drag and skin friction drag are key parameters for determining how much power is required for maximum endurance. For the HALE mission this process is complicated by the fact that the vehicle will be in darkness for a portion of each 24 hour period. Energy reserves must be replenished to be available during the periods of darkness. Electrical power harvest and storage are critical to the success of this facet of the mission performance.

3.1.3 24-Hour Operation

On the issue of continuous 24 hour operation, it is important to keep in mind that the overall weight of the vehicle is directly affected by the amount of power storage capacity that is necessary for day and night operation. Two facets of this challenge are important to highlight:

- During daylight power is required for flight sustainment, payload operation and for replenishment of the stored energy which is consumed during the night.
- Vehicle design is impacted by the weight of the power storage system—system weight dramatically affects takeoff and climb power required—which further affects the weight of the propulsion unit.

More will be said about the innovation of the EPICV design to specifically address these aspects of system performance requirement.

3.1.4 Solar Powered UAV Research

In previous research, NASA investigators analyzed the impact of subsystem technology on an electric UAV's size. Ref. 1 presented an analysis of the impact of power system components and mission requirements on the size of solar powered HALE aircraft. An important finding from this work was the relationship of the energy storage system performance to the vehicle's size. The impact of PV cell performance was found to be less important. The results of this analysis showed that the specific energy value for the storage system must be in the range of 250-500 Whr/kg to support useful missions. One of the stated goals of the cited paper was to examine the remaining power system deficiencies that stand in the way of successful solar powered UAVs. It was meaningful to the present analysis that the results of the NASA investigation so clearly identified power storage (fuel cell/electrolyzer) as a major constraint on electric UAV development. A key finding in the cited analysis was that fuel cell capacity had a far greater influence on wing aspect ratio than did the efficiency of the PV cell system. There is no indication from the information reviewed in Ref. 1 that any investigation was conducted into improving the power consumption efficiency of the propeller/power plant technology. It was mentioned that the motors were samarium electric motors with approximately 90% efficiency. Therefore, it is evident that a challenge still exists for coming up with a motor/rotor combination that shows clear advantage over the present technology.

3.1.5 Fuel Cell/Electrolyzer Development

Fuel cell/electrolyzer state-of-the-art is lagging behind the 400Kwh/kg level reported in the NASA research. Consequently, the challenge is to assess the likelihood that current development efforts will be mature enough in three to five years to support a credible system development. Or, if there is a path for development of a system with less specific energy storage capability, the challenge is to optimize the propulsion system requirements to achieve a compatible power required/power available match in the mission performance scenario.

3.1.6 Attracting Industry Involvement

The ultimate technical challenge is to create an operating paradigm that is attractive to industry. In other words, create a technology, which can be adapted and used comfortably by industry in exploiting the atmosphere-space continuum for commercial enterprise. The present paradigm for telecommunication satellite technology is to rocket launch a satellite and collect revenue based on its throughput capability. The rocket launch phase of this scenario is very expensive to industry. Therefore, the challenge at hand is to create a technology that will enable industry to build their payloads and UAV flight platforms concurrently. They would then launch the hardware from their own industrial facilities with no more requirement than having to file a flight plan with the FAA for the ascent phase of the flight. Attributes of a proposed system will be discussed in the innovation section.

3.2 Payload Margin

In keeping with the goal to create a flight system which has appeal to industry, the payload to gross weight fraction must be as high as possible. Industry must be able to make the business case that using the new technology shows a clear and distinct return on investment. One major market area that would be the fulcrum for getting industry involvement is wireless communication for major metropolitan centers such as: New York, Los Angeles, Chicago, and Atlanta. An EPICV type of vehicle that could be launched and flown at high altitude over the region and act as a communication switching and relay platform has great economic value to industry. Increased bandwidth is already a telecommunication industry goal. Huge sums of money are being invested in fiber optic cable that will address the networked system technology for in-home entertainment and shopping. Services such wireless data and voice remain as challenges for industry.

3.2.1 Margin for Payload Weight

Further research is needed to develop insights into the payload requirements that support future telecommunication systems technology. These requirements must then be used to size a UAV capable of carrying the desired payload above a major population center.

3.2.2 Power Margin for Payload Operation

The HALE mission presents the challenge of 24-hour continuous operations. The problem of energy generation and storage for both flight sustainment and payload operation must be addressed with innovative approaches. In the innovation section a functional concept will be presented that allows the power storage requirement to be dramatically reduced.

3.3 Aeromechanical Efficiency

The approach to achieving a highly efficient aeromechanical design is more involved than just combining the most efficient subsystems and components into one system. For example, the highest efficiency solar cells may only be available in the form of inflexible panels. Applying these panels to the wing would result in a faceted surface, which would suffer from severe turbulent flow and high drag. Consequently, more power would be required to pull the aircraft through the air. If lower efficiency thin film solar cells could be used on a smooth, low drag wing, the cruise power required would be lower and it is possible that the overall system efficiency would be higher.

Sorting out the effects of each component's characteristics on the overall system is a significant optimization challenge. For example, the efficiency of a fuel cell must be traded off against the weight impact it has on the total aircraft and how the overall weight affects the power required for flight. Thus, an iterative process must be established to evaluate the numerous possible design permutations. The process must account for the interdependencies that in some cases are counter productive in a multi-variable problem solution context. An example is in optimization of surface area for solar energy capture-- skin friction drag for the vehicle is increased which increases power required, that may potentially add weight to the propulsion system. Technical approaches supported by analytical methods are needed to support engineering assessments of design tradeoffs.

SECTION 4
TECHNICAL INNOVATION

The previous sections have described a baseline vision of the EPICV. It is fully recognized that, at this stage, there is not enough information on the various technologies to ensure an accurate feasibility assessment of the design approach. Consequently, several innovative technologies will be investigated for use as necessary to achieve the HALE telecommunications relay mission. This section describes those areas of innovation and how they might impact the conceptual design.

4.1 Toroid Rotor

The application of toroid rotors to aerodynamic propulsion is a new concept. Toroid motor/rotor units (MRUs) are currently used in the submersible vehicle industry. Fisher Electronics makes the underwater systems and the vehicle in Figure 4.1 that was constructed for the Navy using toroid MRUs.

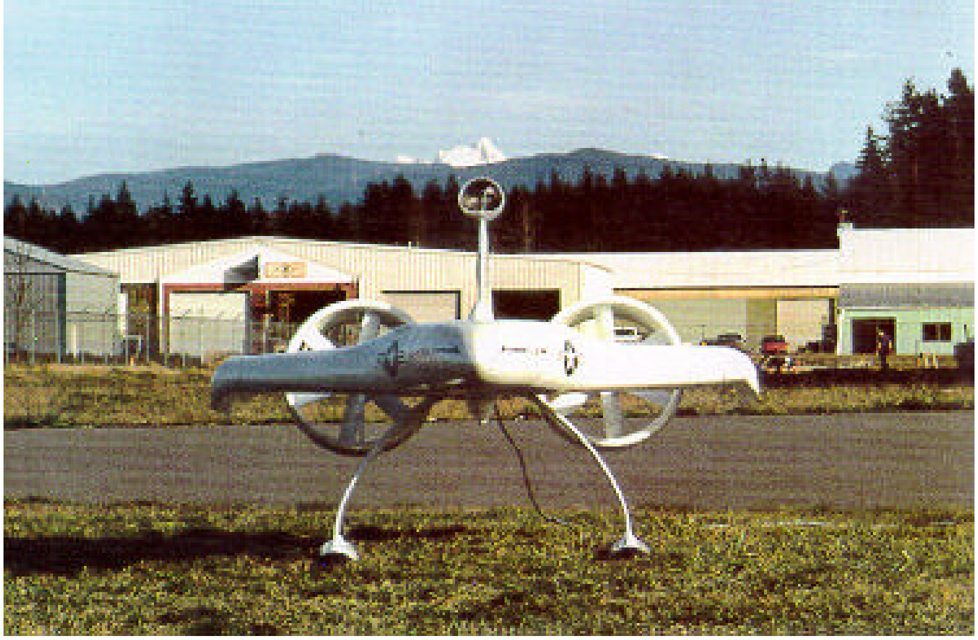

Figure 4.1 Underwater Craft with Toroid Motor/rotor Units

4.1.1 Key Advantages

The primary advantage of the toroid MRU concept is that it has a significant mechanical advantage by being driven from the rotor rim. Consequently, it is capable of delivering high torque. This advantage becomes apparent when considering how power and weight are traded off in rotorcraft design.

The power required sustaining vertical flight is composed of two major components: induced power and profile power. Induced power is the power required to pump enough air downward to offset the vehicle's weight. This power can be determined from a simple momentum model of the rotor system and constitutes about 60%-70% of the power required to hover. The profile power represents the effort required to drag the blade's airfoil through the air. This power is proportional to the square of the blade's tip speed. Typical blade tip speeds range from 500 ft/sec to 800 ft/sec. At higher tip speeds the rotor begins to experience high drag problems due to compressibility effects.

In conventional designs, power is supplied to the rotor by a high speed, low torque engine (or motor). These types of powerplants usually operate most efficiently at 10,000 rpm or more. Driving a rotor of any consequential size directly at these speeds would result in unacceptably high tip speeds. For this reason, a transmission is used to reduce the powerplant's output speed and raise its torque. In small conventional helicopters, transmission reduction ratios on the order of 10:1 – 15:1 are common. This requires a heavy transmission that adds to the overall weight of the vehicle and, thus, requires more power to lift.

Because of its inherent high torque capability, it may be possible to operate the toroid rotor at low enough speeds without the need for a transmission. This represents a significant weight savings and improvement in overall efficiency. Furthermore, because the electric motor is distributed around the duct, no components are located beneath the rotor and incurring a download penalty. Finally, some level of structural efficiency is gained by using the duct for two purposes – aerodynamic control of the rotor inflow and structural support of the electric motor.

Ducted rotors such as the toroid rotor also have an aerodynamic advantage over open rotors in producing thrust. Near the tips of open rotor blades the high pressure air on the bottom surface of the blade rolls around the tip to the low pressure region above the blade. This creates what is known as a tip vortex which reduces the rotor's induced power efficiency. In a ducted rotor, the strength of the tip vortex is greatly reduced because the clearance between the blade tip and wall is very small (0, in fact, for the toroid rotor). As a result, for an open rotor and ducted rotor of equal radius and induced power level, the ducted rotor will produce 26% more thrust than the open rotor. Alternatively, for the same radius and thrust level, the ducted rotor will require 30% less induced power than the open rotor.

Even though it has numerous advantages, the toroid rotor design does have a few disadvantages. One is the drag penalty incurred by dragging the duct through the air during cruise. While tilting the duct to align it with the flow greatly reduces the drag penalty, the impact on cruise efficiency must still be assessed. Other disadvantages are design issues regarding the need for large diameter thrust bearings and lubrication. These are not considered serious and will be addressed during the detailed feasibility and preliminary design studies.

4.2 Integrated VTOL and Fixed-Wing Flight Controls

The EPICV is required to operate in two extreme (and conflicting) flight modes. For takeoff, the aircraft must be able to hover and climb vertically. It must then transition to forward flight mode and proceed to a high altitude, long endurance flight regime. Flight control in the forward flight fixed-wing mode will be accomplished with conventional aerodynamic control surfaces - ailerons, elevator, and rudders. Conventional fixed-wing controls were chosen because they are a low risk, low cost, and low power consumption approach. In contrast, the optimal technique for VTOL mode control is not so clear cut. Appendix A presents a review of the control concepts employed by various VTOL aircraft to illustrate some of the tradeoffs that must be made. The conclusion of the review is that a four-rotor design appears to offer the advantages of mechanical simplicity and vertical thrust efficiency. In this arrangement, the forward and aft rotors are used for pitch and yaw control while the lateral rotors are used for roll control. All four rotors are used for vertical thrust control.

4.3 Circulation Control

The previous discussion on flight controls stated that the initial plan for generating control power in cruise is to use deflecting control surfaces. However, it is known that deflecting the control surfaces will increase it drag on the aircraft and, thus, increase the power requirement. Also, since it may not be feasible to install solar panels on these surfaces, the solar collecting area is reduced. An alternative method for affecting airflow without control surface deflection is circulation control (blowing). Circulation control involves the ejection of a thin jet of air to directly affect the airflow about an aerodynamic surface (Fig. 4.2). The controlling jet of air is supplied by a compressed air source. The jet sheet controls the pressure distribution over the aerodynamic surface and is thus a very powerful method of force generation. The blown sheet remains attached to the curved trailing edge by a balance between the negative pressure differential across the jet and the centrifugal force acting on the curving jet. The resulting flow entrained into the curving jet sheet initially acts as a boundary-layer control (BLC) at very low momentum (blowing) coefficients to prevent separation. At slightly higher blowing, the jet adheres to the round trailing edge, moving the airfoil's stagnation point and streamline well onto the lower surface and acting as a pneumatic circulation control. This greatly augments the airfoil lift well beyond that of mechanical conventional high-lift flap systems, and into the region of Supercirculation with lift coefficients up to 6.5. More importantly, force augmentations on the order of 80 times the blowing momentum input have been observed in tests on 2-D airfoils (i.e. a return of 8000% on investment of useful work).

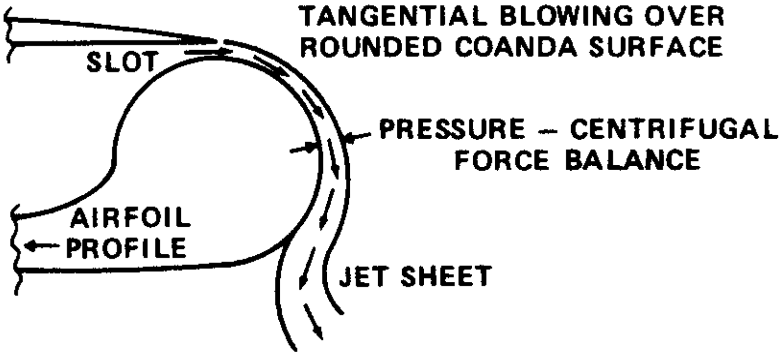

Figure 4.2 Basic Circulation Control Scheme on an Aerodynamic Body

The primary benefit to be gained by using circulation control is that it eliminates the need for actuators, linkages, and other moving parts. This decreases the weight and complexity of the mechanical design. It is also possible to reduce the induced drag on the wing by blowing near the wing tip. The tradeoff that must be examined is the amount of power saved by reducing drag versus the power required to generate the compressed air supply.

The air supply for circulation control can be accomplished by an ingenious design of the toroid rotor. Air is scavenged from a port that is on the tip of the blade nearest the center of rotation. The plan form of the air capture and centrifugal pumping action can be seen from Figure 4.3. In this depiction one can readily see how a pressurized air source can be designed into the toroid motor/rotor unit. The fact that a pressurized air source is available also may provide a mechanical method of moving the heat from the bearings which will be generated at the anticipated RPM of the propulsion units. The fact that the vehicle will be flying at high altitude were air density is unable to support much cooling this may be an effective way to move and redistribute heat for requirements such as maintaining temperature for fuel cell efficient operating environment.

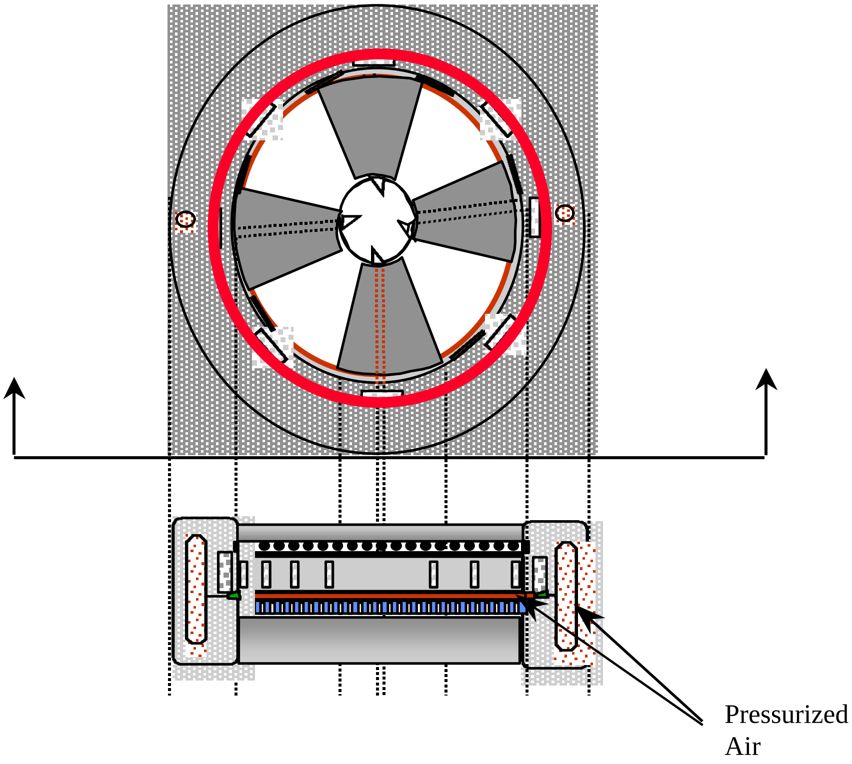

Figure 4.3 Pressurized Air Supply form Toroid Rotor

4.4 Joined Wing Airframe Design

The earlier discussion on the joined wing design outlined many of the benefits of this configuration. The primary benefits are greater structural stiffness and lower induced drag as compared to a conventional configuration. The joined wing also offers several innovative approaches to trimming and controlling the aircraft. In a conventional cruciform design, increased lift is achieved by first deflecting the trailing edge of the elevator upwards to generate a download on the tail. This induces a nose-up pitching moment on the fuselage which increases the wing's angle of attack, thus increasing lift. To balance the overall lift on the aircraft, the wing must produce an additional portion of lift to compensate for the download on the tail. In the joined wing design, both sets of wings produce positive lift and the magnitude can be changed directly without changing the pitch attitude of the fuselage. This can be achieved by collectively increasing the effective camber of both wings by either deflecting flaps or using pneumatic circulation control. The joined wing can also provide direct drag and side-force control as well. This offers the possibility of trimming the aircraft somewhat independently of attitude. Such a capability could be a useful technique in managing the aircraft's incidence angle relative to the sun for optimal solar collection.

4.5 Helicopter Assisted Launch

Realizing that vertical takeoff capability presents a difficult challenge in terms of power demand, an alternative method for launching the EPICV will be investigated. Figure 4.4 illustrates a concept in which a helicopter is used to lift the vehicle and tow it into low speed forward flight. Although this increases the complexity of the launch operations to some extent, it can greatly reduce the propulsion system weight budget because power required for vertical takeoff is avoided and the launch still permits operations without a long runway. What about landing? Vertical landing can be accomplished by designing a surge capability for the electric motors. The toroid motor rpm can be surged for cushioning the vehicle in the very last phase of a controlled descent. This surging feature is unique to electric propulsion. Over-speed of other types of motors usually produces damage resulting in replacement or retirement of the motor

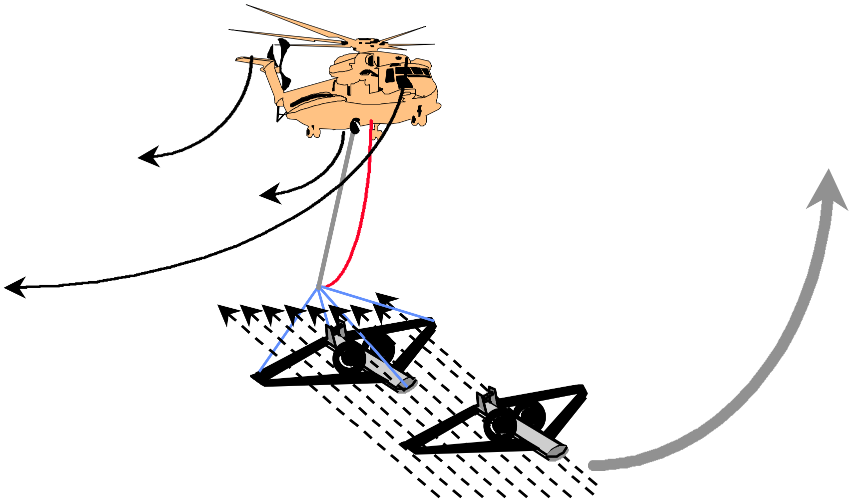

Figure 4.4 Helicopter Assisted Launch

4.6 Wireless Power Transmission (WPT)

Reference 5 provides an extensive survey of space borne power station theoretical discussion and exhaustive historical perspective on technical demonstrations of “beamed power’ from the ground. A very persuasive argument is presented that pivots on the ever-increasing demand for power to support the earth’s ever-increasing population. The technological information presented shows clearly that WPT is the key technology. We have utilized this technology for 40 years in the form of microwave ovens. Even standards have been developed that govern it’s safe use. In 1975, NASA demonstrated a 30KW beam could be transmitted a distance of 1 mile at an efficiency of 82%. WPT was proven to be feasible.

For EPICV application of beamed power this research effort has focused on reversing the path that has been the focus of all previous efforts. The paradigm that has been studied, demonstrated and discussed is a concept based upon ground receivers that are large “antennas” that receive the microwave energy and transform it into electricity. The proposed approach for EPICV is to make the aircraft the target of the energy beam as depicted in **Figure 4.5 Spaced Based Power Supply**. Surprisingly Reference 5 reported on an experiment whereby a helicopter was powered in flight by a microwave beam. The microwave beam was from a ground transmitter. What is being proposed as a result of this research is: beam energy from outerspace into the upper region of the atmosphere, directly on to the EPICV receiving antenna.

It is very exciting to also realize that laser energy has been considered for strategic missile defense. The process of what a space borne missile defense system does and the functional requirement for pointing a beam of energy at a cooperative target for aircraft flight sustainment show tantalizing similarities. In the literature [Ref 5] it is reported that a laser beam traveling through space may do so with very high efficiency—99%. Given that the EPICV would be at an altitude of 70K feet, atmospheric attenuation (loss) would not be as bad as for a beam originating from the ground.

The transmission and reception issues of beamed energy are complex. Admittedly much of the previous work was focused upon up-and-down links for a notional aircraft. However, one experiment in the 1980’s did prove the feasibility of sustaining flight for a drone with beamed microwave energy. This was performed on Canada in 1987. The drone reached altitude under battery power and when locked on to the beam, it turned off its battery and was sustained via the microwave link. See Ref 5 for further details.

Pointing and controlling laser beams has received significant investigation under the aegis of Strategic Missile Defense research. Concentrated and dispersed beams generated by continuous wave electric discharge lasers with recirculating gas have been studied. Gas circulation facilitates removal of excess heat, minimizes power consumption during long periods of operation. Carbon dioxide and carbon monoxide electric discharge lasers have reached advanced development. Other laser concepts including free electron lasers, diode laser arrays and solar pumped lasers are under development. Power may be applied to these lasers by photovoltaics or through direct excitation from solar flux. Photovoltaic cells sensitive to high frequency could be used to convert laser beam energy to d. c. electric output. Potential for interference from laser beamed energy is not an issue as with microwave. However, the chemical reaction of thin atmosphere and possible plasma effects must be studied.

Based upon public information about the functional characteristics available on strategic ballistic missile defense, it is possible that the power system for the missile defense system could serve two purposes—a dual use technology application as it were. A strictly hypothetical concept is suggested by Figure 4.4. The space borne power stations that would necessarily support laser beam firing at a potential target could potential fire a laser beam of specific energy content at an EPICV system at it's operational altitude of 70 thousand feet. The algorithms for tracking the target and pointing the beam will have necessarily been formulated from the early research on weapons operational concept. Further research is necessary to fully develop the potential role that could bridge this very important gap for sustainment energy for high altitude UAVs.

One further dimension to the concept of beaming energy from space borne power stations should be described. That concept is collaborative effort with between NASA and Department of Defense. Since the missile defense system will proceed under separate DOD funding, a collaborative effort should be initiated between NASA and DOD to investigate the possible dual use of wireless power transmission (WPT) technology. From the NASA perspective the notional idea of charging industry a "fee for use" of power should be investigated further. The basic idea of a privately owned UAV using energy captured and beamed by space borne power stations which also have a defense mission is not as far fetched as it may sound. NASA may even consider selling "power-by-the-hour" as a way of recouping some of the developmental costs.

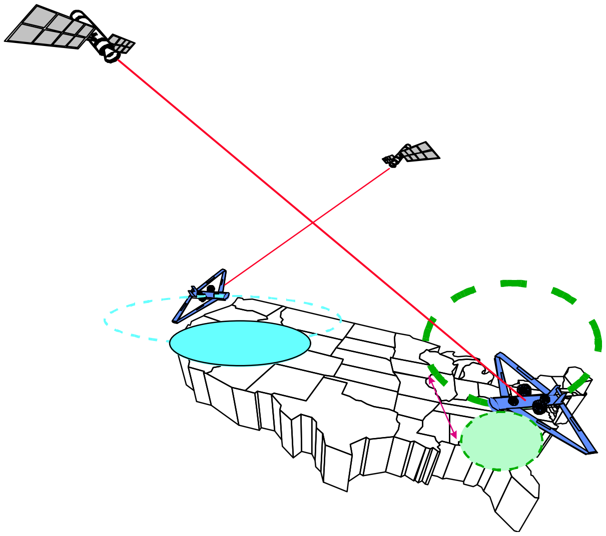

Figure 04.5 Spaced Based Power Supply

Once again, these ideas are preliminary but they have potential merit at this point in the quest for a new paradigm for the application as described. Further study and investigation will be necessary to fully explore the issues related to a future program for the commercial use of UAVs on such a grand scale. The technology components are fragmented and no analytical tools exist that couple the interdependencies so that alternative approaches can be evaluated for the technical and economic merit.

SECTION 5
CONCLUSIONS AND FURTHER STUDY RECOMMENDATION

There are high altitude UAV designs that have flown and shown the technical viability of the concept. It is not clear that designs based upon high aspect ratio wingspan are the optimum blend of propulsion efficiency and airframe design. The results of this research shows that there are technical alternatives that hold forth benefits which will entice the interest of industry and stimulate consideration in the private sector of a whole new approach to wireless communication capacity expansion. This research has shown that there is development activity in the area of fuel cells and electrolyzer systems that will be able to provide power densities needed for continuous (24 hr.) operation.

The investigations conducted to this point have formed the conceptual definition for an autonomous, high altitude air vehicle with a solar powered regenerative power system for telecommunications relay. Next, a more in-depth study must be performed to evaluate the feasibility of the concept and lay out the preliminary design. This will involve a thorough examination of the current technology levels in areas such as solar cells, fuel cells, electrolyzers, batteries, chargers, and electric motors. Also, a number of trade studies must be conducted to select those technologies that offer the highest overall efficiency and will be available within the required timeframe. The tasks for the feasibility and preliminary design studies are outline below.

5.1 Further Study

During the course of the current investigation numerous trade papers, press releases, and advertising literature in various technology areas were reviewed. The published data paints fairly promising portraits of each of the technologies being offered. However, to truly establish the level of capability in areas such as solar cell efficiency or fuel cell efficiency, a more in-depth evaluation must be made. This will require forming cooperative arrangements with the technology developers to gain access to information regarding their shortcomings rather than just their well-publicized successes. Such “inside” information is necessary to gauge the feasibility of using their technology for this unique application.

5.1.1 Solar Cells

- Consult and visit independent experts at the National Renewable Energy Laboratory, Golden, CO and Sandia National Laboratories, Albuquerque, NM.
- Conduct cooperative investigations with various commercial solar cell providers to establish current and projected capabilities.
- Establish database on solar cell characteristics for use in tradeoff studies.

5.1.2 Fuel Cells and Electrolyzers

- Consult and visit independent experts at the NASA Glenn Research Center, Lewis Field, OH and Argonne National Laboratory, Chicago, IL.
- Conduct cooperative investigations with various commercial fuel cell and electrolyzer providers to establish current and projected capabilities for EPICV application.
- Establish database on fuel cell and electrolyzer characteristics for use in tradeoff studies.

5.1.3 Batteries and Chargers

- Consult and visit independent experts at Argonne National Laboratory, Chicago, Il.
- Conduct cooperative investigations with various commercial battery and charger providers to establish current and projected capabilities for EPICV application.
- Establish database on battery and charger characteristics for use in tradeoff studies.

5.1.4 Electric Motors

- Consult and visit independent experts at Aerovironment and Aurora.
- Conduct cooperative investigations with Fisher Electronics to establish current and projected capabilities for toroid motor/rotor units.
- Establish database on electric motor characteristics for use in tradeoff studies.

5.1.5 Telecommunications Satellites

Establish range of expected weight and power requirements for telecommunications payloads serving a large metropolitan area through cooperative investigations with leading satellite manufacturers such as Hughes, Loral, etc.

5.1.6 Telecommunications/Wireless Throughput Requirements

Estimate projected telecommunications throughput requirements within the next 10 – 20 years for candidate metropolitan areas through consultation with telecommunications service providers such as Panamsat, Bell South etc.

5.2 Tradeoff Studies

Tradeoff studies will be conducted using the information gathered through consultation and cooperative investigations. The process will involve determining what simulation models of the various aspects of the EPICV system should be developed to minimize risk and conduct those trade studies.

5.2.1 Aircraft Model

Take NASA's solar powered HALE UAV modeling program and modify it for EPICV (i.e., include effects of ducted rotors, joined wing, etc.)

5.2.2 Power System Model

In conjunction with GTRI's Systems Development Laboratory create power system model of solar cells, fuel cells, electrolyzers, chargers, batteries, electric motors, signal conditioning, flight control computer and actuators, and payload power requirements. In addition to modeling efficiencies, include effects of waste heat and its management.

5.3 Preliminary Design

Use aircraft and power system models to conduct preliminary design of complete aircraft system.

5.4 Collaboration to obtain Spaceborne Power

Once the phase II preliminary design effort is successful, the next step is to seek collaboration on receiving beamed power from power stations developed by DOD or commercial sources. Most probably th power stations will be developed for the Ballistic Missile Defense Program. However there has been a very active voice in calling for movement by NASA to proceed with power station development (see ref. 25). There are other exploration initiatives that will create demand for power, lunar exploration and colonization as well as deep space travel and colonization. Once the EPICV system has been characterized in phase II, research efforts should proceed into the space borne power scenario development.

SECTION 6
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APPENDIX A

A.1 VTOL Control Requirements

The primary requirements for control in VTOL flight are vertical thrust, body pitch and roll attitude control, directional control, and anti-torque. Since a VTOL aircraft operates at speeds below which aerodynamic surfaces are effective, control must be obtained from the propulsion system. In conventional helicopters, the main rotor provides both vertical thrust and the body pitch and roll attitude control. This is accomplished through a swashplate and pitch link mechanism at the rotor hub which can adjust the blades' pitch angle collectively and cyclically. Collective pitch controls the rotor thrust, while cyclical pitch controls the rotor pitch and roll moments. Directional control and anti-torque are provided by the tail rotor which has only collective control for varying the thrust. Control options for ducted rotor and multi-rotor aircraft are discussed in the following sections.

A.2 Single Rotor Unit Aircraft

Examples of single rotor/propeller unit aircraft include the Airborne Remotely Operated Device (AROD) which is a ducted propeller configuration (see Fig. A.1) and the University of Texas Arlington Autonomous Air Vehicle which is an open propeller design (see Fig. A.2). These types of vehicles use a fixed pitch propeller and articulated vanes in the propeller slipstream to achieve control. Thrust is controlled by varying engine speed and torque is reacted by deflecting the vanes in the slipstream. Body attitude and directional control are also accomplished with the vanes. While this design is mechanically fairly simple, it does have some disadvantages. One is that the control power can be somewhat limited if the moment arm from the vanes to the c.g. of the vehicle is short. The result will be that vane deflections tend to result more in a translational acceleration than a moment about the c.g. Increasing the distance from the propeller to the vanes may lengthen the moment arm but it also increases the overall height of the vehicle and, hence, its drag in forward flight. Forward flight speed is another area where this design has its shortcomings. It has already been pointed out that the high drag on the vehicle will limit its top forward speed, but the vanes present an additional problem. In order to be effective, the vanes must be immersed in the slipstream of the propeller. The higher the forward speed of the vehicle, the more the vanes will be affected by the forward flight freestream. Furthermore, ducted rotors and propellers suffer pitch stability problems at high forward speeds due to flow separation over the lip of the duct.

Figure A.1. Airborne Remotely Operated Device

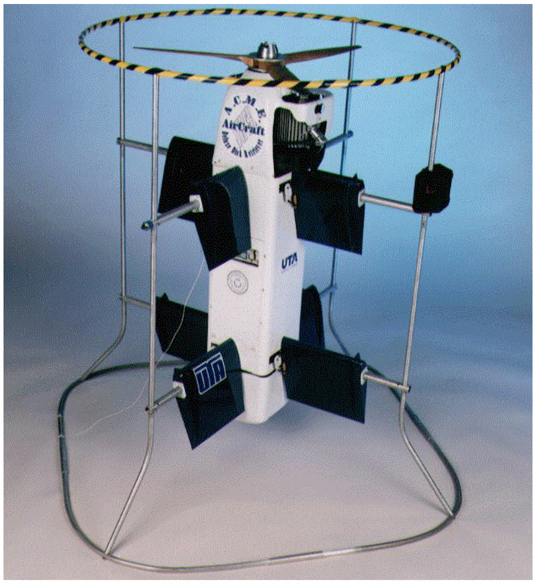


Figure A.2 UTA Autonomous Air Vehicle

Figure A.3 Moller Aerobot

The Moller Aerobot (Fig. A.3) and the Sikorsky Cypher (Fig. 2.6) both employ a single duct housing two counter-rotating rotors. In these vehicles, the counter-rotating rotors eliminate the need for a separate anti-torque device. The Aerobot uses fixed-pitch propellers and thrust is controlled by motor speed. Directional control is achieved through differential thrust (and, hence, torque) on the two propellers. Attitude control is achieved through vanes in the propeller slipstream. The Sikorsky Cypher uses fully articulated rotors with collective and cyclic control such as on a conventional helicopter. Directional control is obtained through differential thrust (torque) and attitude control is achieved through the cyclic pitch inputs to the rotor system. The collective and cyclic control mechanism on the Cypher does make the hub more complex, but it gives the vehicle significantly more control power than would be possible with vanes in the slipstream. It should be noted that because they are ducted systems, these vehicles have the same high forward speed problems as those previously mentioned.

A.3 Multi-Rotor Unit Aircraft

One example of a dual rotor unit aircraft is the Piasecki PA-59 called the “Airgeep” (see Fig. A.4) developed during the late 1950’s and early 1960’s. The vehicle consisted of two ducted rotors arranged in tandem and turning in opposite directions to balance torque. Thrust was controlled by collective pitch on both rotors rather than by engine speed variation with fixed pitch propellers. Although a collective pitch mechanism makes the hub system more complex, this technique is more responsive that engine speed variation ,particularly for piston and turbine engines. In fact, turbine engines must typically be operated within a fairly narrow speed range which, more or less, dictates the use of a blade collective pitch mechanism and engine speed governor.

The body pitch attitude of the Airgeep was controlled by differential collective on the rotors. The body lateral control was achieved with lateral cyclic on the rotors for moment generation and by longitudinally disposed vanes in the slipstream for side force generation. Again, the hub is made more complex by the use of a lateral cyclic mechanism; however, as it was noted earlier, slipstream vanes do not provide adequate roll moment generation because of their short moment arm from the aircraft c.g. Differential deflection of the vanes provided directional control. A later version of the Airgeep (shown in Fig. A.4) had a canted fuselage which placed the rear duct at a smaller inflow turn angle than the forward duct in forward flight. This was done to reduce the momentum drag caused by the sharp turn of the inflow through the

Figure A.4 Piasecki PA-59H, the “Airgeep”

horizontal rotors. Top speed for the Airgeep was approximately 55 knots.
Another dual ducted rotor configuration was the Doak VZ-4 shown in Fig. 2.8. The VZ-4 had laterally disposed, ducted rotors that were tilted vertically for hovering flight then rotated to a horizontal attitude for forward flight. The rotors turned in opposite directions to balance torque. In vertical flight mode, thrust was controlled by collective blade pitch on the two rotors and lateral control was achieved by differential thrust. The body pitch attitude was controlled by reaction jets at the tail of the aircraft. This simplified the design of the rotor hub (in that no blade cyclic control mechanism was used) by shifting the complexity to the jet reaction control system. Directional control was by differential deflection of vanes in the rotor slipstream. Because the ducted rotor units on the VZ-4 rotated to a horizontal position, it could achieve high speed flight without suffering the problems of vertically oriented ducted rotors in forward flight.

Another dual rotor system VTOL configuration is the tiltrotor. Examples of this type include the XV-15 (see Fig. 2.9) and the V-22. Like the VZ-4, these aircraft use tilting rotors to achieve both hover and high speed flight. Their rotor systems employ conventional helicopter rotor controls, i.e., collective and cyclic blade pitch mechanisms. Thrust is controlled by collective blade pitch on both rotors, while roll is controlled by differential collective (thrust) on the rotors. The aircraft pitch attitude is controlled by longitudinal cyclic and yaw is controlled by differential longitudinal cyclic on the rotors. Lateral cyclic is available to translate the aircraft laterally with very little body roll. While the use of conventional helicopter rotor controls makes the hub system quite complex, it provides the aircraft with exceptional control power and makes it highly maneuverable.

One type of a three rotor system aircraft is the tiltwing, of which the CL-84 is an example (see Fig. A.5). The configuration consists of two large lifting propellers rigidly attached to a rotating wing and a small propeller or ducted fan at the rear of the vehicle. The lifting propellers have collective control only and are used together to control thrust and differentially to control roll in VTOL mode. The small propeller or ducted fan in the tail is used for pitch attitude control and does not contribute significantly to vertical thrust on the vehicle. This pitch fan has collective control only for varying thrust, which, in turn, changes the pitching moment about the c.g. of the aircraft. This arrangement simplifies the design of the main rotor hub by eliminating the cyclic pitch mechanism and shifting the complexity to the tail pitch fan. Directional control is obtained from the differential deflection of flaps in the slipstream. Since torque on the small pitch control rotor is low, the overall torque is balanced by having the two main lifting rotors turn in opposite directions.

Another tri-rotor system concept is the GTRI Traffic Surveillance Drone (Fig. A.6). The design for this vehicle consists of a single, large, horizontally mounted lifting rotor and two smaller forward-facing ducted propellers (called propulsors). The lifting rotor employs a swashplate for conventional helicopter collective and cyclic control. This provides for thrust control as well as the body pitch and roll control. The propulsors have collective control for varying thrust. Differential thrust on the propulsors is used for anti-torque and for directional control. Collective thrust on the propulsors is used for forward flight propulsion. A tail boom with horizontal and vertical stabilizers is also included because of concerns regarding the pitch stability of ducted rotor systems in forward flight.

Figure A.5 Canadair CL-84 Tiltwing

Figure A.6 GTRI Traffic Surveillance Drone

An example of a four rotor unit vehicle is the first generation AROD shown in Fig. A.7. In such configurations it is possible to use fixed-pitch propellers and to control thrust through motor speed. Differential thrust on the fore and aft rotors would provide body pitch control. Likewise, differential thrust on the laterally disposed rotors would provide roll control. Differentially deflected vanes in the propeller slipstream would provide directional control.

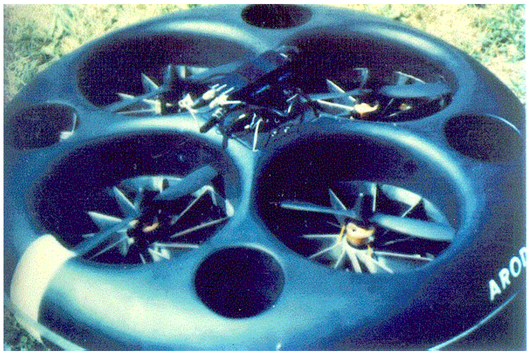


Figure A.7 First Generation Airborne Remotely Operated Vehicle

A.4 Discussion

The foregoing description of the control techniques employed by various VTOL air vehicles illustrates several tradeoffs that must be made. In general, the main tradeoff is between mechanical simplicity and control power. Several systems attempt to achieve mechanical simplicity by having no rotating frame controls (i.e., swashplate and pitch links) and relying on moveable vanes in the slipstream instead. As pointed out earlier, the main disadvantage to this approach is that the vanes tend to produce side forces rather than moments about the aircraft's c.g. due to the short moment arms. Attempts to increase the moment arms simply make the aircraft taller and, thus, increase its drag. Furthermore, the vanes are adversely affected by wind gusts and freestream flow in forward flight.

Another approach to keeping the rotor system mechanically simple is to use multiple rotors. In such configurations the moment can be generated by differential thrust on the rotors. The design can be further simplified with fixed-pitch propellers if engine speed variation is feasible for controlling thrust. This is certainly the case for aircraft powered by electric motors such as the first generation AROD. Multi-rotor unit aircraft tend to employ an even number of lifting rotor units as means of balancing torque. This eliminates the need for an auxiliary anti-torque rotor (such as on a conventional helicopter) that does not contribute to the overall lift of the vehicle.

With regard to the EPICV, the conceptual performance analysis led to the requirement for two relatively large tilting motor/rotor units. Two rotor units were chosen (as opposed a single larger unit) to balance the torque on the vehicle without the use of a non-lifting auxiliary rotor. Since these main lifting units are electrically powered, it is quite feasible to use motor speed variation to control thrust with a fixed-pitch propeller. Roll control can be achieved by differential thrust on the two laterally disposed main lifting rotors when they are in the VTOL position.

While it would be possible to control pitch from the main lifting rotor units, it would require the addition of a cyclic pitch change mechanism to the hub such as that used on the tiltrotor configuration. This would circumvent the goal of rotor hub mechanical simplicity. As stated earlier, vanes in the slipstream of the main rotor units would not generate sufficient moments because of the short moment arm to the aircraft c.g. A tail pitch fan such as that used on the tiltwing is an obvious solution. However, if a simple fixed-pitch propeller design is preferred, pitch control will require two longitudinally arranged rotor units- one at the nose and one at the tail of the aircraft. This is because a propeller with fixed-pitch can not generate negative thrust (without reversing the motor which is not a desirable approach). Thus, two rotor units providing differential thrust are required for pitch control. This approach has the added advantage of allowing the pitch control rotor units to also contribute to the vertical thrust on the vehicle. Their contribution would certainly help in lifting the vehicle off the ground vertically. In forward flight, pitch control can be achieved with a conventional tail mounted elevator and the fore and aft pitch fans can be shut down. This would eliminate the potential pitch instability associated with ducted rotors in forward flight. The main lifting rotors would not be susceptible to this pitch instability because they are tilted forward with increasing airspeed and remain in primarily axial flow.

Directional control on the UAV can be accomplished with vanes in the slipstream of the pitch control rotor units. In this axis (longitudinal), the vanes would have a fairly long moment arm to the aircraft c.g. which should be near the center of the body. Furthermore, the vanes would be oriented longitudinally which would minimize their impact on aircraft drag. In forward flight, once the aircraft's speed is high enough to transfer control to the rudders, the vanes could be folded flat to close off the pitch rotor ducts and further decrease the aircraft drag. Some studies will have to be conducted to determine if this arrangement can provide enough directional control power particularly when the long joined-wings are attached. It is possible that vanes may have to be placed laterally in the main lifting rotor's slipstream to generate the required directional control power. The effect of these vanes on aircraft drag should be minimal since the vanes will rotate with the rotor unit and remain aligned with the air flow.

A.5 Conceptual Control Law Design

Given the range in flight environment (from low altitude VTOL to high altitude cruise) and the changes in configuration, the EPICV will require a fairly sophisticated automatic control system. This control system will have to handle the transition from control with thrusters in VTOL mode to control with aerodynamic surfaces in forward flight mode. Also, ease of operation will be essential, requiring the automation of some functions such as MRU tilt, attitude stabilization, and, perhaps, waypoint following.

The control law design will follow the classical single loop closure approach with multiple levels of feedback loops. The methodology is well understood and a significant number of analysis tools are readily available. While the application of more modern control law design techniques such as neural networks and fuzzy logic may be intriguing (especially from an academic viewpoint), the classical approach tends to have lower risk when designing for new vehicle types. Since the dynamics of a new aircraft type are not usually fully known, the classical approach allows the designer to focus on the effects of each feedback loop on the aircraft's response. Understanding the effects of the feedback gain and being able to adjust it for individual loops provides much need flexibility in dealing with the disparity between the linear models used for control law design and the nonlinear dynamics of the actual vehicle. This is one of the reasons the classical approach was used for designing the fly-by-wire control laws of the V-22 tiltrotor.

The control laws envisioned for the EPICV consist of (from innermost to outermost loops): body rate feedback for stabilization, attitude feedback for attitude hold and turn coordination, velocity feedback for airspeed hold, and position feedback for hover hold and waypoint following. The following paragraphs describe the planned control law format for each aircraft axis. These control laws were developed as part of an earlier simulation effort involving the CH-53 helicopter (Ref. A-9315). The control laws were used in conjunction with a trajectory command generator to “fly” a high fidelity, nonlinear dynamic model of the CH-53 through a series of prescribed maneuvers. The goal of the effort was to determine the rotor system loads during maneuvers.

A.5.1 Longitudinal (Pitch) Axis

The longitudinal axis baseline control laws are designed for rate command/attitude hold using a proportional plus integral body rate inner loop (see Fig. A.8). The body pitch rate is fed back through a first order lag to minimize the control system's response to high frequency oscillations in the range of the rotor dynamics and wing structural dynamics. The time constant for the filter will be set to roll off the rate signal above 10 rad/sec to eliminate feedback at frequencies higher than the handling qualities frequency domain. If the frequencies of the wing structural modes are lower than 10 rad/sec, a notch filter may be required to prevent interaction between the control system and the wing structural response.

The aircraft's pitch attitude is held whenever zero body rate is commanded and the actual body rate falls within a "capture" window. The attitude hold is released when a nonzero body rate is commanded. Attitude error signals are fed through a first order lag to prevent the control system for exciting higher frequency modes. This permits good low frequency tracking on attitude while minimizing the destabilizing effect that attitude feedback can have.

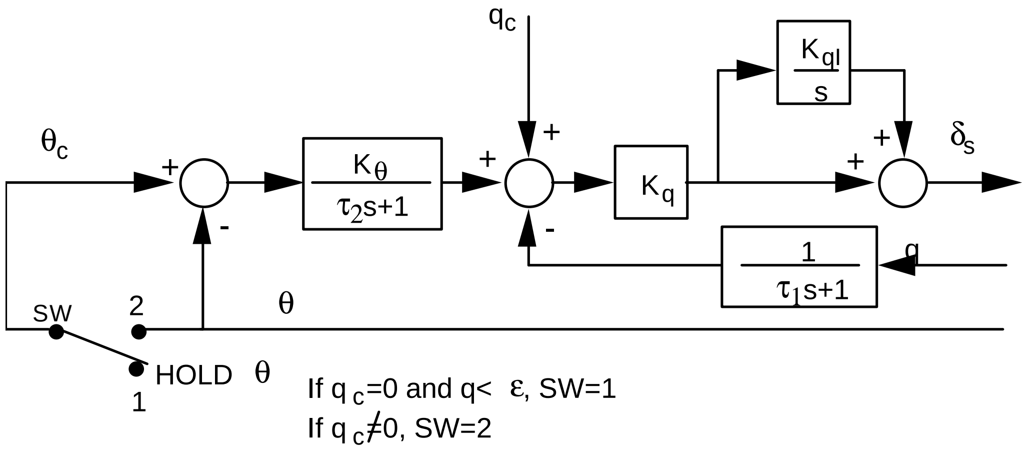


Figure A.8 - Pitch Axis Baseline Control System

An additional outer loop closure is made to the pitch axis to feed back longitudinal speed for a velocity command system. Fig. A.9 shows the addition of the outer velocity command loop to the RCAH structure. Velocity feedback is inertial based from a GPS sensor rather than airspeed based. Using inertial based velocity allows the velocity command system to operate in the low speed regime where an airspeed sensor becomes inaccurate. Note that when the velocity command loop is engaged, the attitude feedback loop is opened.

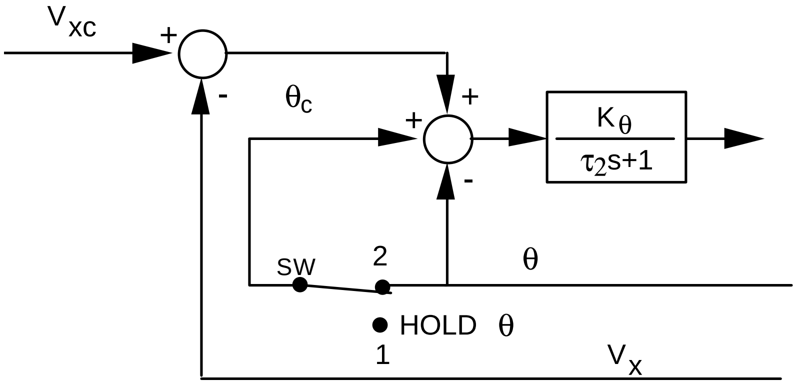


Figure A.9 - Longitudinal Velocity Command Loop

Other outer features will be added to the baseline longitudinal controller to provide:

1. Position Hold - An inertial position feedback loop to maintain position as part of a hover hold function

2. MRU Tilt/Pitch Decoupling - A feedforward command proportional to the MRU tilt rate to reduce the pitching moment due to inertial coupling as the MRUs are rotated

3. Airspeed Scheduled Elevator Rigging - Variable stick-to-elevator rigging for desired pitch sensitivity throughout the speed envelope

4. Auto Conversion - Automatic MRU tilt conversion scheduled with airspeed to keep aircraft inside the conversion corridor

A.5.2 Lateral (Roll) Axis

The lateral axis baseline control laws are also designed for rate command/attitude hold using a proportional plus integral body rate inner loop (see Fig. A.10). Like the pitch axis, the body roll rate is fed back through a first order lag to minimize the control system's response to high frequency oscillations in the range of the rotor dynamics and wing structural dynamics. The aircraft's roll attitude is held whenever zero body rate is commanded and the actual body rate falls within a "capture" window. The attitude hold is released when a nonzero body rate is commanded. The low speed lateral velocity command loop is shown in Fig. A.11. Variable stick-to-aileron rigging will be used for desired roll sensitivity throughout the speed envelope

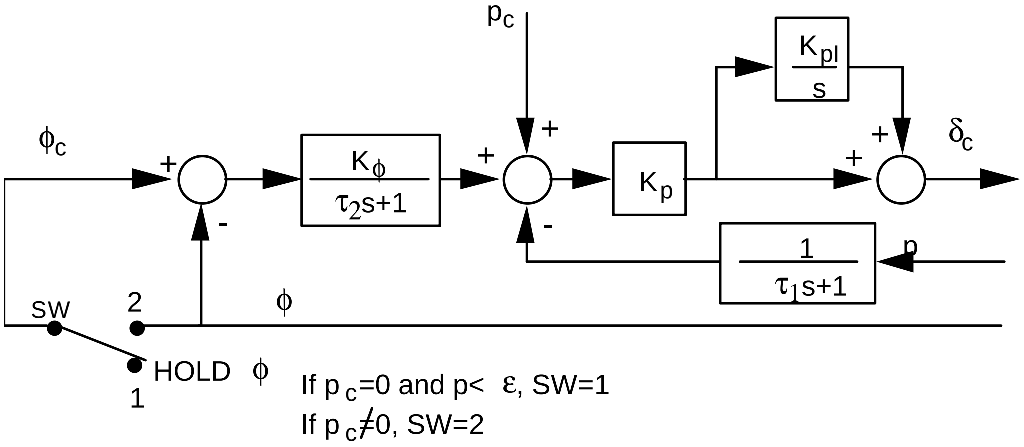


Figure A.10 - Roll Axis Control System

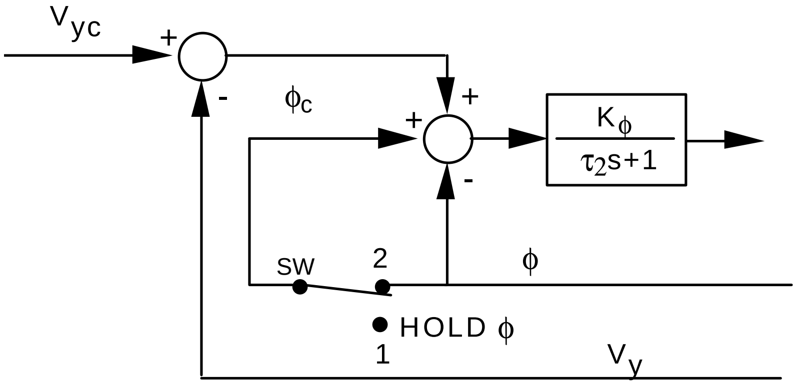


Figure A.11 - Lateral Velocity Command Loop

A.5.3 Directional (Yaw) Axis

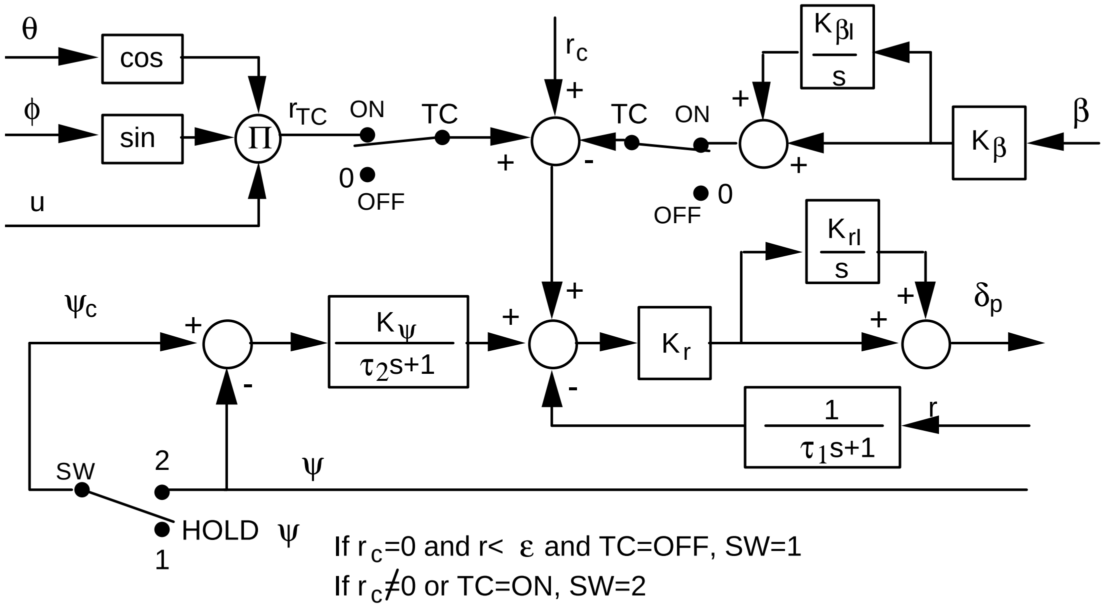
The directional axis control is based on the same rate command, proportional plus integral structure as the pitch and roll axes loops (see Fig. A.12). A turn coordinator is also provided that automatically applies yaw rate commands to minimize the lateral acceleration in a turn. The yaw rate command for turn coordination is derived using the equation for lateral acceleration:

$$a_y = \dot{v} + ru - pw - g\cos\theta\sin\phi$$

where a_y is the lateral acceleration, u, v, and w are the longitudinal, lateral, and vertical body velocities, respectively, p and r are the roll and yaw rates, and θ and ϕ are the pitch and roll attitudes, respectively. In a coordinated turn it is desired to have $a_y = 0$ and $\dot{v} = 0$ and for a steady turn, $p = 0$. Solving for the turn coordination yaw rate yields

$$r_{TC} = \frac{g}{u}\cos\theta\sin\phi$$

Sideslip is also fed back to coordinate the turn. Airspeed scheduled rudder rigging will be used for desired yaw sensitivity throughout the speed envelope.



If r_c=0 and r< ε and TC=OFF, SW=1
If r_c≠0 or TC=ON, SW=2

Figure A.12 - Yaw Axis Control System

A.5.4 Vertical (Thrust) Axis

The vertical axis employs rate command type system based on vertical rate feedback with altitude hold (see Fig. A.13).

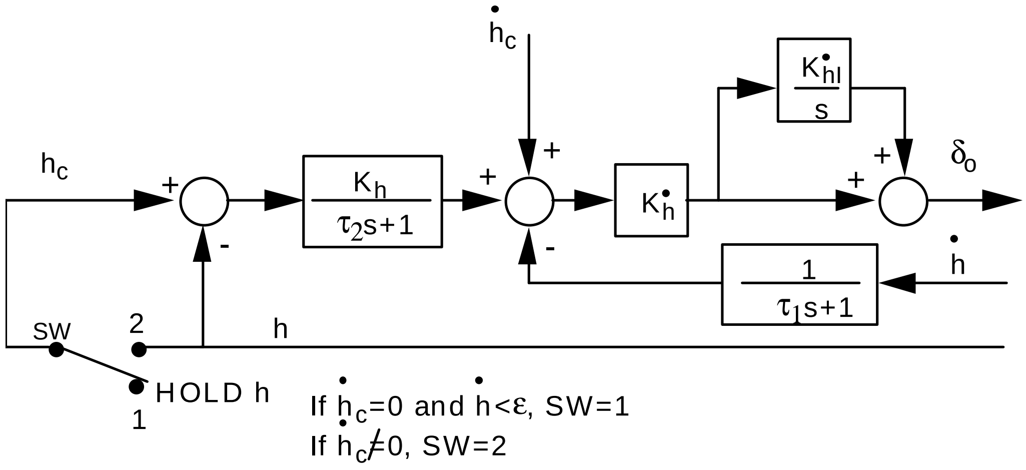


Figure A.13 - Vertical Axis Control System

A.6 Control Law Development

Control laws will be developed for the EPICV in an iterative fashion as illustrated in Fig. A.14. The initial set of control laws will be developed using a six degree of freedom simulation model based on analytical equations. This simulation will use estimates of the vehicle's mass, c.g., moments of inertia, aerodynamic properties, and control effectiveness to model the aircraft's dynamic response. The model will be updated with more accurate representations with the results from bench tests, wind tunnel tests, and free-flight tests.

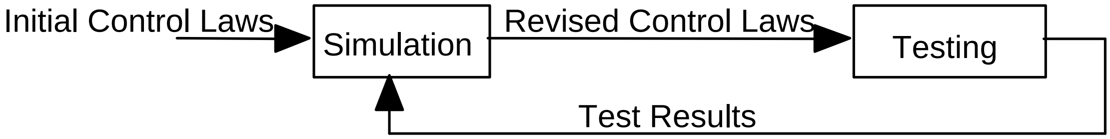


Figure A.14 - Control Law Development Process

Bench testing will include frequency domain tests to determine the bandwidth of the control system. These tests will be conducted by applying a sinusoidal input of varying frequency to the control system and measuring the response of the system. Using frequency domain system identification techniques, the control system model parameters can be determined including bandwidth, damping, and phase (time) delays. This type of testing is essential in order to design a control system that is not so slow as to be sluggish nor so fast that it excites structural modes or becomes unstable.

Wind tunnel testing will be required to determine the aerodynamic characteristics of the vehicle. Although these tests will be conducted under static conditions, crucial dynamic model data, such as control sensitivity derivatives, can be obtained. These tests will also provide the necessary data for the aircraft's performance model.

Frequency domain testing of the vehicle in free (or tethered) flight will be necessary to obtain values for the modeling parameters that are functions of the body rates and accelerations. These tests can be conducted with an initial set of control laws under tightly controlled conditions. The results from the test will be used to update the simulation model which will then be used to upgrade the control laws. Development will proceed in this fashion until up-and-away flight is achieved.