EVA
Tilt-rotor Electric Vehicle for Twenty-First Century Atmospheric Flight

NASA SBIR 2005 PROPSAL

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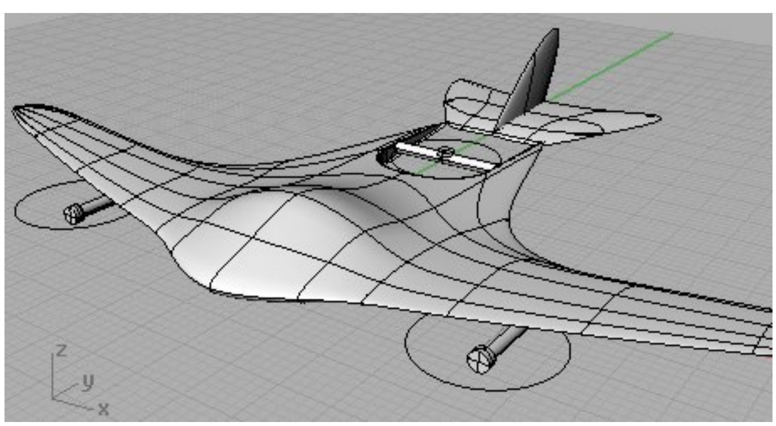

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Part 2: Identification and Significance of the Innovation.

This study introduces a revolutionary atmospheric flight concept by combining tilt-rotor with electric drive technology. The motivation and significance of this innovation is the capability to takeoff and land vertically anywhere, with a machine that also cruises efficiently. The proposed Electric VTOL Aircraft (EVA) will have two predominate flight modes: “normal” flight mode and hover-mode. Hover mode, which is used for takeoff and landing uses an on-board 6 degrees of freedom inertial management system to greatly assist the pilot’s control of pitch, roll, and yaw. Takeoff and landing can be a single lever event. Electric drive motors facilitate system control because they are readily controlled through electronics and also because of the high torque and nearly instantaneous thrust provided by the electric drive motors themselves. This unique flying machine has the potential to revolutionize general aviation in a number of ways including zero emissions, very quiet operation, vertical takeoff and landing, efficient cruise, affordability, and safety through redundant motors and dual landing modes to name a few.

There are a multitude of viable configurations for the electric tilt-rotor aircraft. Two embodiments are shown here, both renderings show the aircraft in hover mode. In each case the front most motors are tractors and the rear motor(s) are pushers. The thrust elements (motors and propellers) are arranged so that the center of lift of combined thrust is coincident with the center of gravity and close to the center of lift for the wing. Figure 1 shows a possible four motor design and figure 2 shows a possible three motor design.

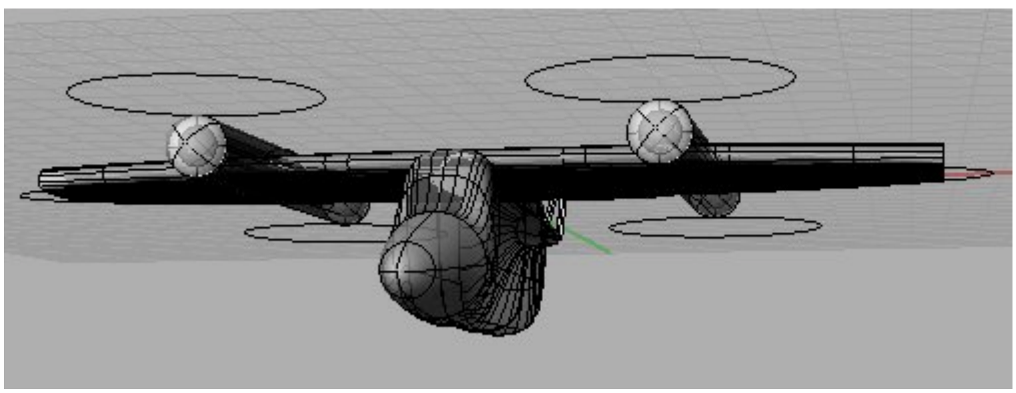

Figure 1. Four motor design in hover mode.

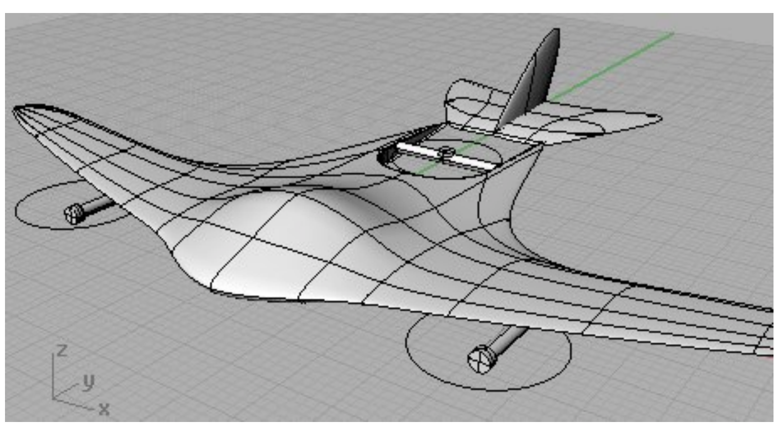

Figure 2. Three motor embodiment.

Figures 3 and 4 show the four motor embodiment in cruise configuration. All four motors are in forward thrust tilt angle, the front motors pulling and the rear motors pushing. Yaw control for coordinated turns can be accomplished through varying the thrust to the left or right motors and also through the use of the rudder. Pitch can be controlled through a combination of thrust vectoring (slightly tilting the motors) and through the use of a conventional elevator. Thrust vectoring can also be used to trim the aircraft for optimal cruise efficiency. Note the size of the wing with area that is lower than conventional light aircraft. Wing loading can be higher to provide efficient cruise parameters at the same time it is large enough to allow conventional landing during emergency situations.

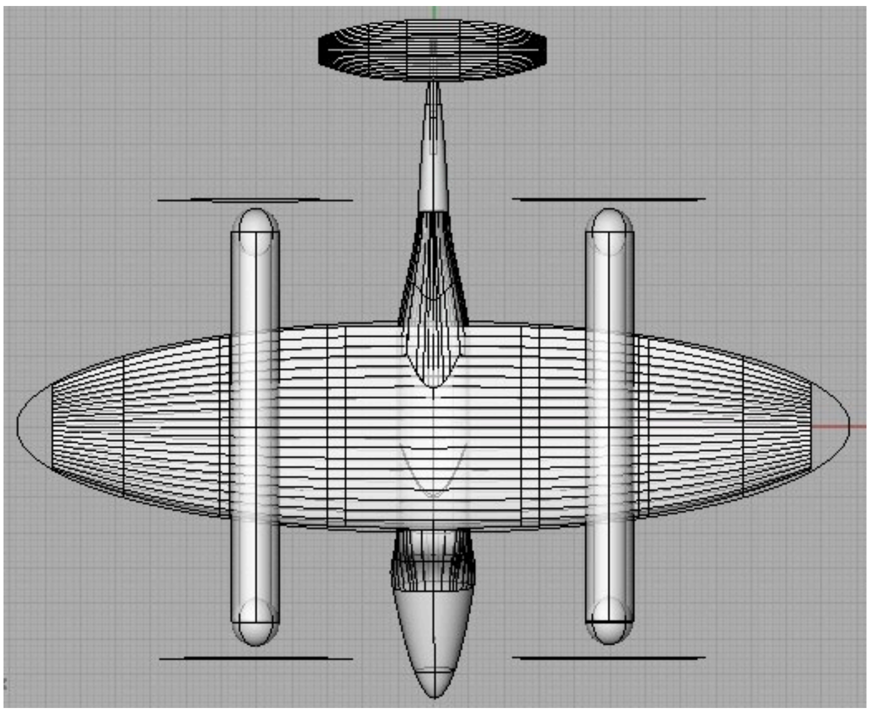

Figure 3 Four motor planform in cruise mode

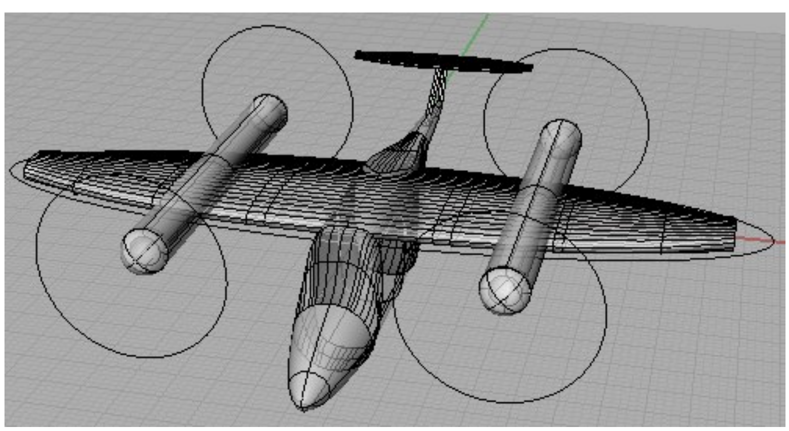

Figure 4 Four motor perspective in cruise mode

An interesting feature of the hybrid or electric aircraft can be exploited to conserve additional energy and that is regenerative descent. During descent from cruise altitude, the motors can act as generators and capture some of the kinetic energy by recharging batteries. Phase 2 of the project will investigate this and other advanced features of the design.

Hover mode is shown schematically in figure 5. The front motors (tractors) are tilted 90 degrees such that the thrust produced is vertical and the rear motors (pushers) are tilted 90 degrees such the thrust produced is also vertical, but down in “pusher mode”. This configuration was chosen to give four legs (or three legs in the case of a three motor design) of stability and also so that the motor rotation direction does not have to be reversed between modes. The onboard inertial computer can easily maintain a level attitude by modulating the thrust produced at each motor. Yaw will be controlled either through minor adjustment to the tilt angle and / or through gyroscopic action by speeding up and simultaneously slowing down diagonally opposing motors. This technique uses conservation of rotational inertia to perform “yaw on a dime”. For example to perform yaw to the right (clockwise rotation in the diagram) the rate of rotation of motors 1 and 3 would be increased while the rate of rotation of motors 2 and 4 is decreased. The overall thrust is balanced maintaining altitude, but the change in rotation causes the aircraft to yaw right.

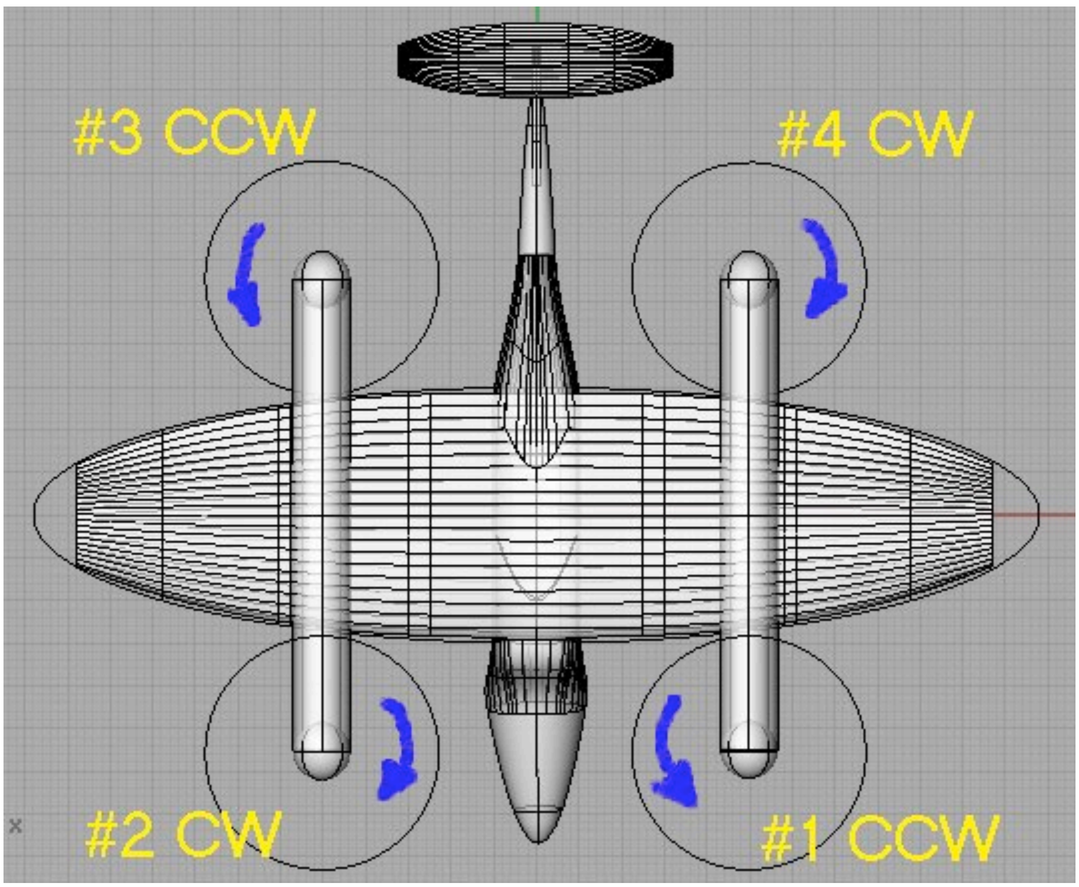

Figure 5 EVA – hover mode planform

Schematic diagram of control and power systems are shown in Figure 6. This general concept is that each motor is driven by its own motor controller which is supplied current from a local battery. Batteries through the controllers supply peak demand currents during takeoff and transition. Location of the controllers and batteries is important to keep heavy high-demand wiring runs as short as possible. Motor tilt is also controlled by the pilot through the pilot assist computer which is not shown in the schematic. Energy source (Fuel cell or turbine) supplies sufficient current to the motor controller / batteries to maintain reasonable cruise rates and achieve viable range.

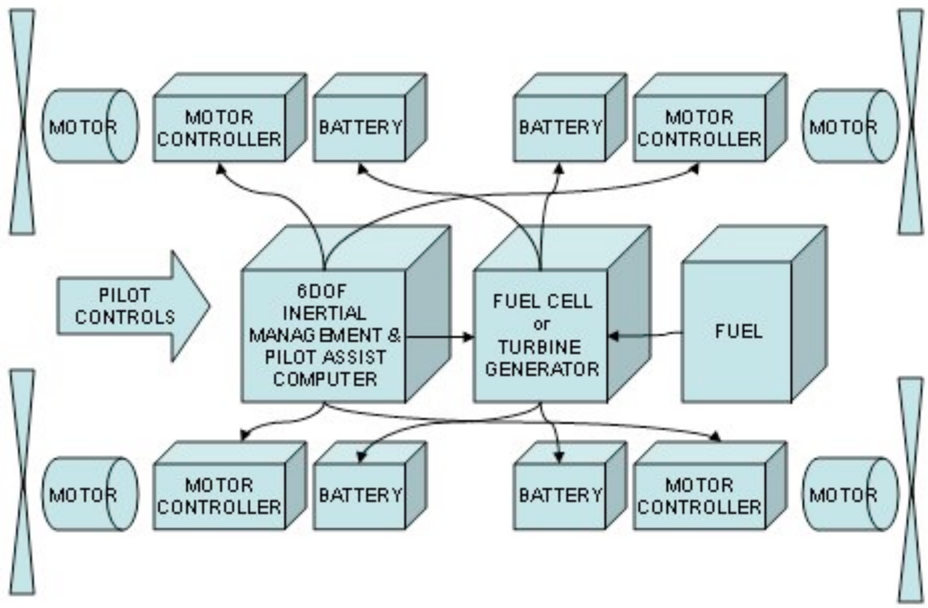

Figure 6 Schematic of control and power systems

A number of key advantages of the EVA concept for general aviation light aircraft are list here and described further in the following paragraphs.

1) Vertical takeoff and landing
2) Zero emissions (with fuel cell option)
3) Quiet operation
4) Efficient cruise allowed by smaller wing area and vectored thrust
5) All electronic inertial management and pilot assist
6) Regenerative descent
7) Dual landing modes for safety
8) Lower initial and operating costs
9) High reliability (drive motors have one moving part)
10) Potential for multiple energy sources

Vertical takeoff and landing is the most obvious benefit and allows efficient point-to-point travel. NASA's "highway in the sky" air traffic control system along with aircraft such as EVA will make air-taxi service a practical reality.

Electronic control systems and electric drive motors work naturally together. Instantaneous and accurate thrust control is possible. Electric motors do not suffer from variability associated with fuels, air pressure and temperature. Their performance does not suffer at altitude. Additionally because EVA will utilize direct drive motors, the large rotational inertia associated with turbine based, or geared tilt-rotor systems are not present.

Electric drive motors have much lower noise. Propeller noise may be the only factor in the noise generated by this type of aircraft. Electric drive motors have lower vibration which leads to lower fatigue on aircraft components and also contributes to lower noise operation. Electric drive motors have smaller footprint, lower mass, and smaller frontal area than typical GA reciprocating engines. The smaller frontal area allows better streamlined design and lower drag.

Additional level of safety is provided by the wings, multiple drive motors and three landing modes. Under normal flight conditions, EVA will land in hover-mode. In the event of power out or motor failure, EVA can be landed in a conventional manner but with higher stall speed than most small GA aircraft.

The wing can be designed for efficient cruise. Vertical takeoff and landing capability provided by the tilt-rotor technique implies that the wing area can be reduced. Flight-mode landing would only be used in emergency situations and as such the designed stall-speed of the aircraft could be increased. Typical stall speeds for light GA aircraft are in the range of 50 to 60kts. This stall speed is usually the parameter that dictates the size (and drag) of the wing. For example, increasing the design stall speed from 60kts to 80kts results in a wing that is nearly half the size. The smaller wing will increase cruise speed, lower fuel burn-rate and generally make the aircraft more efficient.

Vectored thrust can be used to optimize cruise attitude minimizing control surfaces further reducing drag. A degree of trimming can be accomplished by fine-tuning the tilt angle of the motors. This is a level of control that conventional aircraft do not have and could be exploited to maximize efficiency especially in cruise.

Potential for lower upfront and operating costs. Electric drive motors for vehicle applications are currently in less than $7/kW and electronic drive components (motor controller in the schematic) are in the range of $5/kW. Assume that the full scale EVA used four 80kW motors, also assume that advances are made and the advanced motor / control system costs more than the current estimates. If the motor, controller combination cost $20/kW, the total drive system components for EVA would cost $6,400 ($20*80*4). Contrast this figure with the cost of a single engine for an experimental two seat airplane which is roughly $32,000.

Quiet operation. Noise is very important especially for an aircraft that can land virtually anywhere. Homeland Security and Law Enforcement may find a battery-only “stealth mode” very desirable.

Energy sources for electric aircraft are continually being developed and refined (references 1,3,4,5 in part 5). Electric drive flight vehicles such as EVA can use modular power sources. Initially hybrid designs are envisioned to utilize compact, lightweight turbine based alternators to provide current for cruise power and batteries for takeoff, landing and backup power. As advances are made in high energy density fuel-cells and fuel containment, then true zero-emission aircraft can be realized. With the uncertainty relating to energy on the horizon it makes logical sense to decouple advances in propulsion from advances in energy and fuel sources.

Advanced Technology and Future Topics will be explored. Phase-2 can investigated advance concepts of hybrid aircraft including regenerative descent. Akin to regenerative braking in electric / hybrid cars, regenerative descent will recharge batteries during descent to recapture some of the energy used during climb. An additional area to explore is flexible adaptive blade pitch propellers.

Part 3: Technical Objectives.

There are four primary technical objectives for phase 1 R&D:

1) design and build a working model and proof of concept vehicle
2) demonstration of flight showing both modes of flight and transitions between them
3) feasibility study of full scale prototype including preliminary design
4) identification of components, technology and refinements needed for phase 2

The questions to be answered by this R&D work and new concept flight vehicle are: Can it be done?, Can the electronic inertial management system provide sufficient pilot assist for hover mode?, Can the transitions between flight modes be smooth and acceptable? Does this vehicle concept scale effectively up to a two to four passenger aircraft? What are the estimated performance characteristics of the passenger aircraft?

Part 4: Work Plan.

The EVA work plan is presented here in outline format showing the detailed steps to be taken during the phase-1 development. The proof-of-concept vehicle is to be a scaled radio controlled aircraft with wingspan of approximately 36 inches. Weeks shown in the outline are man weeks. PI indicates steps to be performed by the PI.

1) Design of concept vehicle (PI 2 weeks)
    a) Design and selection of size and plan form of vehicle
    b) Design of controls for both modes
    c) Selection, acquisition and testing of drive components (motors, controllers, propellers, batteries)
2) Construction of concept vehicle (PI 2 weeks)
    a) Acquisition of materials and parts
    b) Assembly of airframe and mechanical components
    c) Assembly of wiring harness
    d) Installation of servos and motors (including testing of thrust and tilt functions)
    e) Installation of control system
    f) Determine weight and balance requirements
    g) Installation of batteries
3) Design of control systems (PI 7 weeks)
    a) Design or acquisition of micro-processor based inertial-management system
    b) Interfacing control systems to inertial-management system
    c) Acquire development system hardware and software based on selected microprocessor
    d) Development of software systems for pilot-assist inertial management system
        i) Architecture of EVA operating system (top level control routine)
        ii) Radio command decoding (read radio signal and interpret commands from pilot)
        iii) Reading gyro and accelerometer sensors
        iv) Filtering sensor readings (most likely Kalman filtering)
        v) Controlling of actuating servos and motor drive electronics
        vi) Testing and debug
4) Pre-flight testing (PI 2 weeks)
    a) Construction of test-stands and tethering systems for early flight tests (contracted)
    b) Tethered flight tests
5) Flight tests (PI 3 weeks)
    a) Initial un-tethered flight tests
    b) Incremental improvements of control systems
    c) Secondary flight tests with focus on transition between modes
    d) Further adjustments to control systems if necessary
    e) Tertiary flight tests with video taping for proof of concept

   f) Document results of steps 1 through 5
6) Full scale prototype preliminary design and feasibility study (PI 4 weeks)
   a) Select planform and motor configuration
   b) Size aircraft and propulsion system
   c) Identify components and potential suppliers
   d) Identify components that need additional development
   e) Identify suitable energy sources
   f) Estimate aircraft performance and characteristics
   g) Document findings

Non-flight development and testing will be performed at the offices of ATTOMIC at 1000 Creso Road, Spanaway, WA. Flight tests will be performed at Spanaway Airport at 203 - 188th St E, Spanaway, WA.

Part 5: Related R/R&D.

Over the past two years, Mr. Tibbitts has studied aircraft design and has investigated research related to electric drive aircraft. The design of circuits and programming of microcontrollers are consider routine due to his previous development work. To this date no funded aircraft related R&D activities have taken place. Applicable technical references have been review and include the following:

1. Berton, J.; Freeh, J,; and Wickenheiser, T.: *An Analytical Performance Assessment of a Fuel Cell-Powered, Small Electric Airplane.* Novel Vehicle Concepts and Emerging Vehicle Technologies Symposium, sponsored by the Applies Vehicle Technology Panel of the North Atlantic Treaty Organization Research and Technology Agency, Brussels, Belgium, April 7-10, 2003
2. Kascak, A.; Brown, G.; Trudell, J.: *Ironless High-Power-Density Permanent Magnet Electric Motors Design for Emissionless Aircraft Propulsion*, NASA Research and Technology 2004.
3. Freeh, J.; Liang, A.; Berton, J.; and Wickenheiser, T.: *Electrical Systems Analysis at NASA Glenn Research center: Status and Prospects*. To be presented at the Symposium on Novel and Emerging Vehicle and Vehicle Technology Concepts, organized by the Applied Vehicle Technology Panel of the NATO Research and Technology Agency, Brussels, Belgium, April 7, 2003
4. Kohout, L.; Schmitz, P: *Fuel Cell Propulsion Systems for an All-Electric Personal Air Vehicle*, Prepared for the International Air and Space Symposium and Exposition cosponsored by the American Institute of Aeronautics and Astronautics and the International Council of the Aeronautical Sciences, Dayton, Ohio, July 14–17, 2003
5. Wickenheiser, T.; Sehra, A.; Seng, G.; Freeh, J.; Berton, J.: *EMISSIONLESS AIRCRAFT: REQUIREMENTS AND CHALLENGES,* NASA John H. Glenn Research Center, AIAA/ICAS International Air and Space Symposium and Exposition, 14-17 July 2003, Dayton, Ohio.
6. *Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes*. FAR Part 23, Federal Aviation Administration, January 2003.
7. Katz, J.; Plotkin, A.: *Low-Speed Aerodynamics, second edition*, Cambridge University Press, 2001.
8. Raymer, D: *Simplified Aircraft Design for Homebuilders*, Design Dimension Press, 2003.

Part 6: Key Personnel and Bibliography of Directly Related Work.

Stephen Tibbitts is the developer of the EVA concept and will be the principle investigator during both phase 1 and phase 2. He holds a bachelor of science degree in electrical engineering is a private pilot and member of the Experimental Aircraft Association. Mr. Tibbitts is the founder three successful startup companies PICCO (which is now a part of Broadcom) and Silicon Reality which was purchased by Evans & Sutherland (known for flight simulation) in 2001, and ATTOMIC where he is currently president. Most of his career has been in design and management of microelectronics. Future thinking, project planning, technical project management and tenacity are his strengths.

Much of the phase-1 effort revolves around the design of electronic control systems, writing and adapting code for the onboard flight computer. These tasks will be carried out by the PI, who is well versed both in circuit design and programming of microprocessor systems. As a private pilot Mr. Tibbitts has a firm understanding of flight dynamics which is required for control systems design.

Regarding eligibility, Mr. Tibbitts may submit one additional proposal for 2005 NASA SBIR. In the event that both proposals are awarded Mr. Tibbitts will split his time evenly between the two activities. Note that the projects are somewhat related, but not overlapping. Fifty percent or more of Mr. Tibbitts' time will be allocated to this project.

Phase-1 will leverage existing aerodynamic designs and will seek to find suitable structures to adapt. Off the shelf components will be used wherever possible to facilitate development and provide the prototype as efficiently as possible. Mechanical aspects of the project will be performed by Christopher Tibbitts. Chris has a Mechanical Engineering degree (BSME) and specializes in carbon fiber components.

Part 7: Relationship with Phase 2 or Future R/R&D.

It is anticipated that Phase 1 will prove that this new flight vehicle concept is feasible and will illustrate a path to full scale design which will provide a solid foundation for full scale vehicle prototype in Phase 2. Phase 1 provides a foundation for Phase 2 in the areas basic aircraft configuration, pilot control design, control systems design, inertial management system, flight transition, and preliminary design for a full scale vehicle.

Phase 2 will turn the concept design into a full set of construction drawings. The full scale vehicle will be simulated extensively and refinements will be made to the design where necessary. Required components that do not exist will either be created in-house or developed by subcontractors. Redundancy and safety features will be added to the control systems. These systems will be simulated in both operational and failure modes.

Part 8: Company Information and Facilities.

ATTOMIC owns and operates engineering consulting services at 1000 Creso Road, Spanaway Washington (about 20 minutes south of Tacoma, near the Boeing Frederickson Plant). The company owns all of the equipment necessary to perform the Phase 1 work including: laboratory power supplies, oscilloscopes, measurement equipment, in-circuit emulators, computer, programming environment software, NASA WIND CFD (computational fluid dynamics) software simulator, scales, microscopes, electrical and mechanical design software, saws, drills and other tools.

Projected Phase 2 and Phase 3 activities will require the construction or leasing of additional 2400 square foot hanger and shop space (at company's expense) and the purchase of additional equipment and tooling.

The PI has experience raising significant amounts of capital for start-up operations. Upon entering into a Phase 2 agreement, ATTOMIC will identify and engage suitable industrial partners for sales, marketing and channel development activities.

Part 9: Subcontracts and Consultants.

Design and construction of the pre-flight tethering system will be sub-contracted to Chris Tibbitts. This is estimated to take one man week at an hourly rate of $40/hr or total of $1600.

Part 10: Potential Post Applications (Commercialization).

Applications for EVA are numerous and range from Homeland Security to air taxi service. Where developed countries have highway systems that are overcapacity and emerging countries do not have highway systems EVA makes practical sense. The time has come to add the third dimension to intercity and intra-city travel. Quiet, zero emissions vehicles will be the preferred choice. ATTOMIC seeks to accelerate the development of advanced technologies for VTOL electric aircraft.

Near term research applications for EVA include the development and refinement of technologies needed for the advancement of zero-emission aircraft. Such refinements include very high power density non-cryogenic electric drive motors, very high power density motor control systems, onboard inertial management pilot assist for VTOL aircraft. EVA represents a practical application for advance materials such as carbon fiber composite, metamaterials such as carbon nanotube composites, and possibly other high temperature superconductors.

Post phase 2 applications for EVA include search and rescue and law enforcement vehicles. Ultimately everyone has a version of EVA parked in their double car garage…

It is the authors hope that the cost of EVA can be controlled within the range of a moderately priced sports car through the use of intelligent modular design and mass production techniques. If this can be accomplished then the economic impact is enormous. Collectively we developers need to get aircraft on the same curve as consumer electronics which get smaller, lighter, cheaper and more powerful every year. The GA aircraft industries performance has been dismal over the last twenty years as indicated by the graph provided by the General Aviation Manufacturers Association. Nevertheless, it is an eight billion dollar industry.

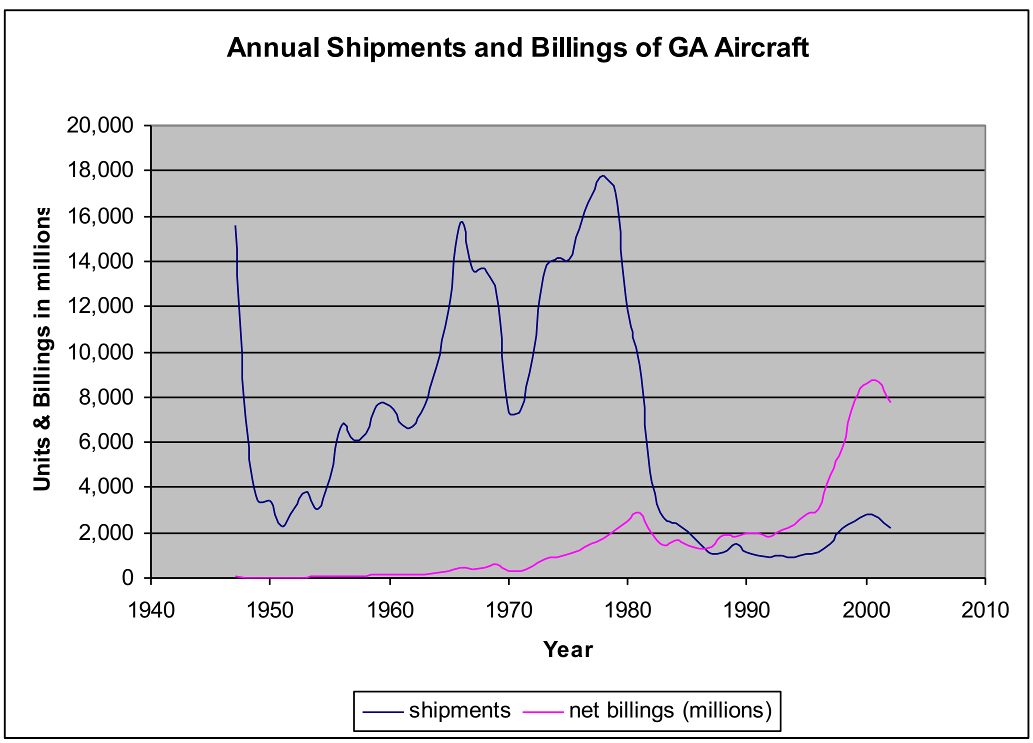

Figure 7 Aircraft Annual Shipments

The Aircraft Owners & Pilots Association (AOPA) provided the information in Figure 8. Of note in this graph are 1) the growth of the experimental category (which is likely to accelerate due to the new light sport aircraft regulations), and 2) the flat-line, zero growth rate for small piston driven airplanes.

EVA has a chance of making general aviation safer, quieter, more convenient and less expensive. These qualities will allow this technology much deeper market penetration than we have seen in the past.

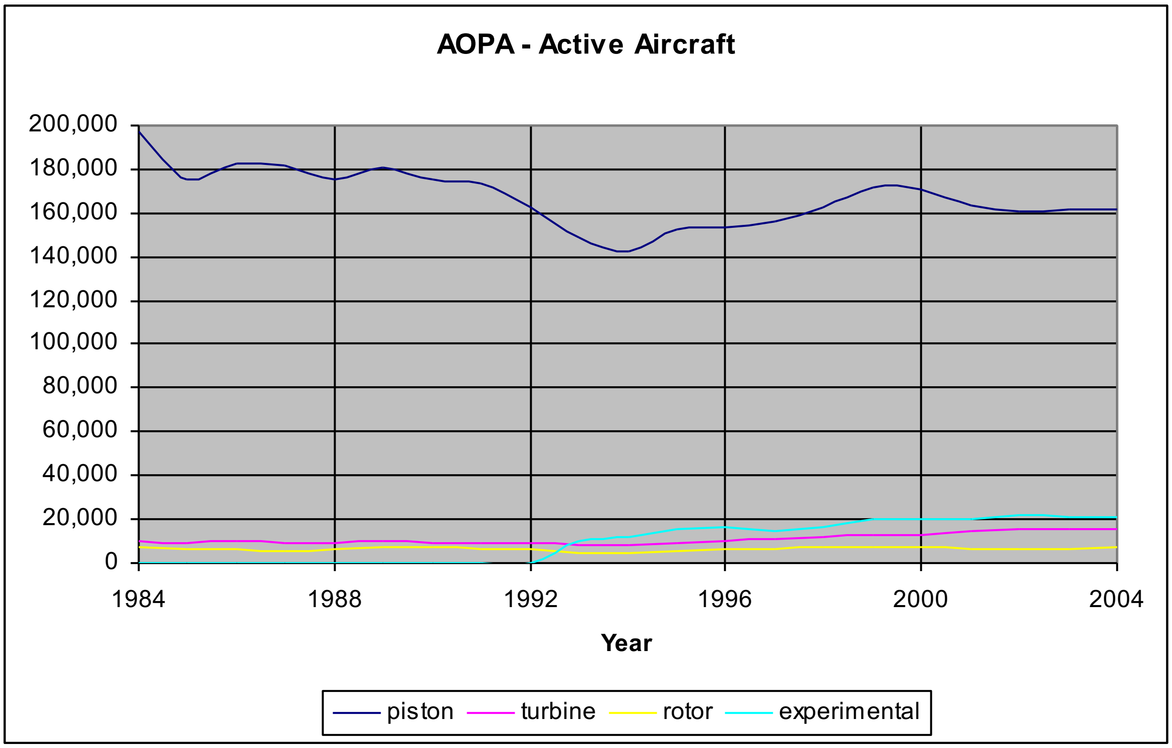

Figure 8 AOPA Active Aircraft

Please note that Phase 2 will provide much more extensive market projection data in the final report.

Part 11: Similar Proposals and Awards.

"Not Applicable."