# PRELIMINARY DESIGN STUDIES OF AN ADVANCED GENERAL AVIATION AIRCRAFT

S5-05
160581
p. 12

## THE UNIVERSITY OF KANSAS

Preliminary design studies are presented for an advanced general aviation aircraft. Advanced guidance and display concepts, laminar flow, smart structures, fuselage and wing structural design and manufacturing, and preliminary configuration design are topics to be discussed. This project was conducted as a graduate-level design class under the auspices of the KU/NASA/USRA Advanced Design Program in Aeronautics. This paper will present the results obtained during the fall semester of 1990 (Phase I) and the spring semester of 1991 (Phase II).

### NOMENCLATURE

| | |
|---|---|
| ACQ | Acquisition |
| AEP | Airplane estimated price |
| APT | Advanced Personal Transport |
| ATC | Air traffic control |
| C/A | Coarse/acquisition |
| CAT | Category |
| COM | Communications |
| DEU | Drive electronics unit |
| DISP | Disposal |
| DMU | Digital memory units |
| EMI | Electromagnetic interference |
| FAA | Federal Aviation Administration |
| FBL | Fly-by-light |
| FBW | Fly-by-wire |
| GA | General aviation |
| GPS | Global positioning system |
| HERF | High-energy radio frequencies |
| HSNLF | High-speed natural laminar flow |
| HUD | Heads-up display |
| IFR | Instrument flight rules |
| IGG | Integrated GPS/Glonass |
| ILS | Instrument landing system |
| INS | Inertial navigation system |
| KU | The University of Kansas |
| LCC | Life cycle cost |
| LCD | Liquid crystal display |
| MAC | Mean aerodynamic chord |
| MAN | Manufacturing |
| NAS | National Airspace System |
| NAV | Navigation |
| NLF | Natural laminar flow |
| OPS | Operations |
| RDTE | Research, development, testing, and evaluation |
| RPM | Rotations per minute |
| SSSA | Separate surface stability augmentation |
| T-O | Take-off |
| USRA | Universities Space Research Association |
| VFR | Visual flight rules |

### 1. INTRODUCTION

Since 1945, when Beech Aircraft corporation came up with the Model 35 Bonanza, speed and range performance of GA airplanes have not improved to any significant extent. With few exceptions, GA airplanes of today are still turbulent flow airplanes. Laminar flow airplanes are now feasible.

Flight control systems of today's GA airplanes are still the same as those of 50 years ago: cables, pulleys, and bell-cranks: this represents 2-3% of the design takeoff weight of the airplane. In addition, tailoring mechanical control systems to today's handling quality requirements is fraught with problems, most of these caused by friction and cable-tension problems associated with mechanical control systems. By switching to a fly-by-light or fly-by-wire system, much of this weight and all of the handling quality problems can be eliminated.

Cockpit instrumentation has been improved since 1945 only in the sense that the instruments are more capable and marginally more reliable. The typical GA cockpit has anywhere from 150 to 300 clocks, bells, whistles, and switches. In terms of airplane design takeoff weight, this amounts to 3-10%. Revolutionary cockpit design would start from scratch: with an empty panel. Through a functionality analysis that gives priority to user friendly features, a new cockpit design should emerge with only very few displays, bells, whistles, and switches. This should eliminate a lot of weight and complexity. Heads-up displays should be considered as a replacement of all existing displays.

Navigation and communication with the FAA's ATC system in today's GA airplanes is very cumbersome and extremely user unfriendly. Since 1945 the ATC environment has grown more and more hostile toward GA airplanes. Most of these procedures can and should be automated through the use of onboard microprocessors. ATC coupling with GPS/Glonass should be considered. Optical disk storage of en-route and terminal guidance should be considered.

Airplane structural design and manufacturing is still done mostly with conventional riveted aluminum materials. Recent developments with Arall (Aramid-aluminum), Glare, and other types of composite materials opens the way to significantly lighter structures. The recently developed outside-in tooling approach makes it possible to design even aluminum structures with surface tolerances that allow for the attainment of laminar flow. In addition, electrical signal and power paths should be integrated into the structure so that these paths also carry part of the air loads.

The flight controls in GA airplanes are still so-called "rate command control systems." The potential exists to change this to attitude or decoupled response command systems. This is, in fact, the logical way to proceed if FBL and/or FBW are used.

This would lead to the complete elimination of many accidents that are fundamentally caused by the rate command nature of today's flight controls.

The purpose of this paper is to present the preliminary design results of an advanced aircraft design project at the University of Kansas. The goal of the project was to take a revolutionary look into the design of a general aviation aircraft including those items mentioned above. This project was conducted as a graduate-level design class under the auspices of the KU/NASA/USRA Advanced Design Program in Aeronautics. The class is open to aerospace and electrical engineering seniors and first-level graduate students. This paper will present the results obtained during the fall semester of 1990 (Phase I) and the spring semester of 1991 (Phase II). References 1 through 17 are reports documenting the work completed in Phase I and references 18 through 25 document the work completed in Phase II.

## 2. PRELIMINARY SIZING

A market survey was conducted to create a database of information that could be used as a reference in preliminary design work. It was also used to identify and compare current and potential designs that would offer competition for the planned design, provide specific aircraft information characteristics to aid in configuration design and development, and identify potential voids in the current market. The market survey included 16 aircraft that were considered to be potential competitors for the planned design in the 4-10 passenger range. The two main competitors in the survey were considered to be the Piaggio P-180 Avanti and the Socata/Mooney TBM-700. Performance data for the 16 aircraft were collected. These data included range, number of passengers, maximum cruise speed, rate of climb, and service ceiling. By plotting the range vs. number of passengers for the 16 aircraft, voids in the general aviation market were located. The Advanced Personal Transport (APT) was selected to be a 6-passenger aircraft capable of a 1200-n.m. range. The average values of selected performance parameters for the 16 aircraft are listed in Table 1.

The mission specifications were selected to make the APT competitive with those aircraft studied in the market survey. The mission specifications are 6 passengers, 175 lb each, with 30 lb of baggage each; range of 1200 n.m. with reserves of 10% mission fuel; 420-kt cruise speed; takeoff field length of 2000 ft at sea level conditions; landing field length of 2500 ft at sea level conditions; maximum rate of climb of 4000 ft/min; twin turboprop powerplant; 8000-ft cabin at 45,000 ft; FAR 23 certification; and 45,000-ft service ceiling.

TABLE 1. Average values of performance parameters.

| | |
|---|---|
| 7575 lb | Empty weight |
| 13244 lb | Maximum takeoff weight |
| 55.2 psf | Maximum wing loading |
| 2.73 lb/lb | Maximum power loading |
| 2730 ft | Takeoff field length |
| 3797 ft/min | Maximum rate of climb |
| 389 kt | High-speed cruise |
| 1858 n.m. | Maximum range |
| 38000 ft | Service ceiling |
| $4 million | Cost |

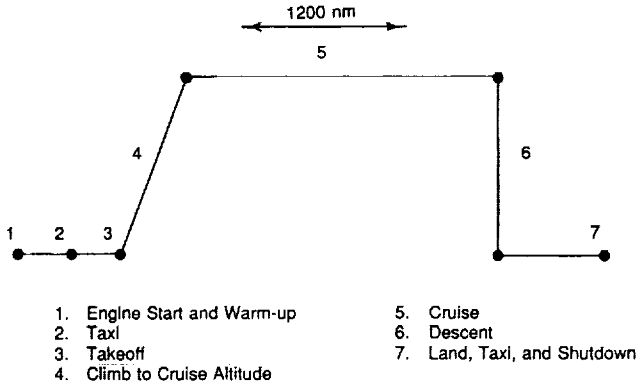

Fig. 1. Mission Profile.

The mission profile is shown in Fig. 1.

## 3. CONFIGURATION DESCRIPTION AND CABIN LAYOUT

Two configurations, a tractor and a pusher, were designed to meet the mission specifications. A twin-boom three-surface configuration was selected for the APT pusher layout. This configuration provides a high degree of structural synergism by allowing the aft pressure bulkhead, wing carry-through mount, and main landing gear mount to form one integral fail-safe unit. Recent research(26,27) has shown that, for the same basic geometry, three-surface configurations typically have a higher trimmed lift-to-drag ratio than either conventional or canard configurations. The research has also shown that three- surface layouts can have lower trim drag over a wider center of gravity range than do two-surface layouts. Flap-induced pitching moments can be automatically trimmed by incorporating a flap on the canard that is "geared" to wing flap deflection.

A three-view and table of geometry of the final design is shown in Fig. 2. One of the primary features of this layout is that it was designed to attain a high extent of NLF. All flying surfaces use NLF airfoils, and the fuselage features a pusher propeller and smooth NLF forward fuselage. The wing is swept forward 15° (measured at the leading edge), and features a midwing location to decrease fuselage interference drag. A strake is incorporated at the wing root to stiffen the wing root against the high torsional loads inherent with forward swept wings. The strake also provides local strengthening for tail boom support and increases the available volume for fuel.

The horizontal tail was located at the top of the vertical tails to place it above the propeller slipstream, which reduces structural noise and fatigue and should allow attainment of natural laminar flow on the tail surface. Ventral fins mounted on the underside of the tail booms insure against prop strikes if the airplane is over-rotated. A standard retractable tricycle landing gear arrangement was selected, with the nose gear retracting forward into the nose and the fuselage-mounted main gear retracting aft into the area underneath the wing. Crosswind landing gear is used to allow the APT to land in a crabbed

Table of Geometry of the Pusher APT Configuration

| | Wing | Horiz. Tail | Vert. Tail | Canard |
|---|---|---|---|---|
| Area (ft$^2$) | 130 | 31.7 | 38.6 | 8.0 |
| Span (ft) | 36.0 | 11.9 | 6.5 | 7.8 |
| Aspect Ratio | 9.97 | 4.5 | 1.1 | 3.8 |
| Sweep Angle | -15°(@L.E.) | 0° | 40°(@L.E.) | 0°(@0.10c) |
| M.A.C. (ft) | 3.28 | 2.6 | 4.2 | 1.00 |
| Taper Ratio | 0.35 | 1.0 | 0.4 | 0.70 |
| Dihedral Angle | 3° | 0° | 90° | -5° |
| Incidence Angle | 1° | 0° | 0° | 3° |
| Twist Angle | 0° | 0° | 0° | 0° |
| Airfoil | Custom NLF Section | " | " | " |
| Thickness Ratio | 0.13 | 0.09 | 0.09 | 0.11 |
| Control Surf. Chord Ratio | 0.25 | 0.30 | 0.32 | N/A |
| Control Surf. Span Ratio | 0.72-1.00 | 0-0.98 | 0.20-0.85 | N/A |
| Flap Chord Ratio | 0.25 | N/A | N/A | 0.35 |
| Flap Span Ratio | 0.19-0.72 | N/A | N/A | 0.21-1.00 |

| | Cabin | Fuselage | Overall |
|---|---|---|---|
| Length (ft) | 11.17 | 29.33 | 34.75 |
| Max. Height (ft) | 4.67 | 5.42 | 9.92 |
| Max. Width (ft) | 4.58 | 4.92 | 43.40 |

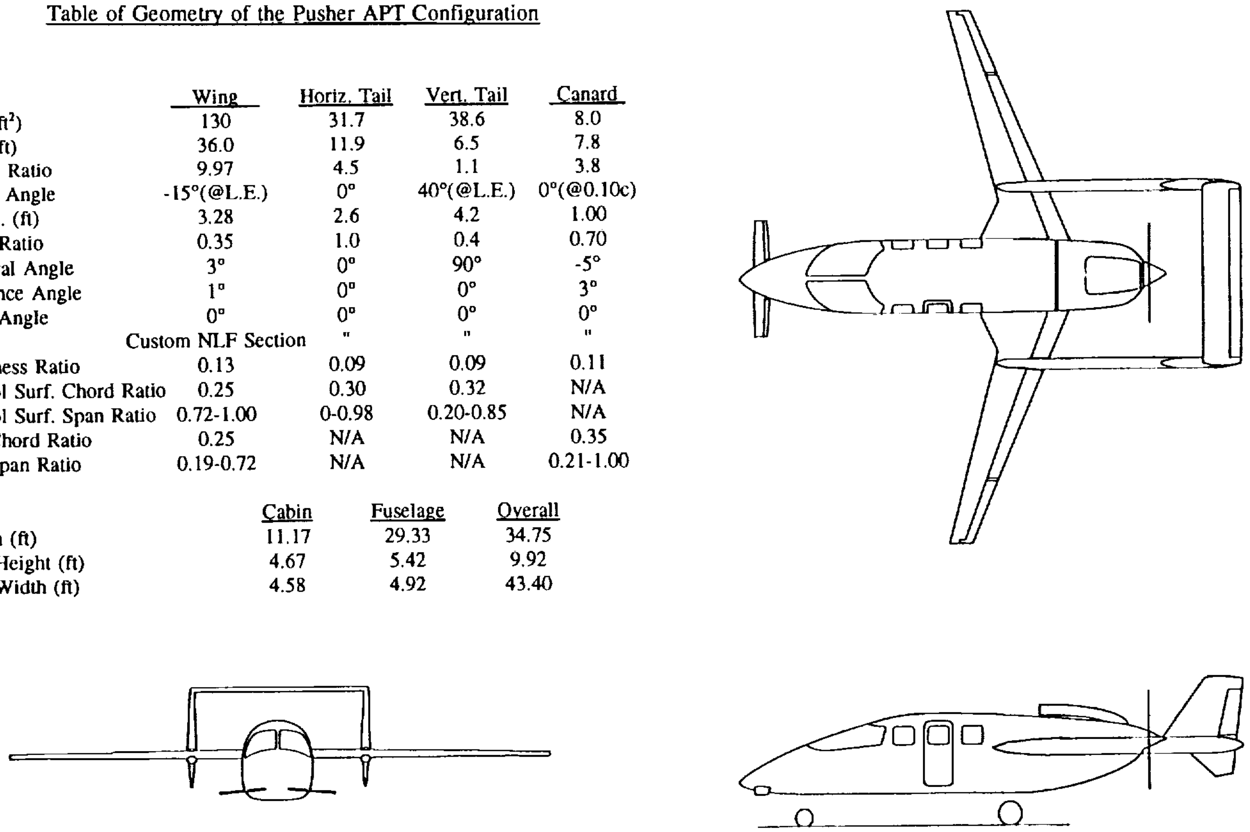

Fig. 2. Three-view of the APT pusher configuration.

configuration. Cabin access is provided by an air-stair door on the left fuselage, which is a convenient feature usually found only on larger turboprops and business jets.

A conventional configuration was selected for the APT tractor layout. This layout provides good balance and flexible wing placement. It should also reduce development costs due to the extensive database of similar airplanes. A three-view and table of geometry of the tractor layout are shown in Fig. 3. As can be seen, the layout is rather conventional and is similar to many popular GA airplanes.

To allow a fair comparison with the pusher configuration, the tractor configuration uses the same cabin layout (Fig. 4) and wing geometry. However, the pusher design was iterated to meet the mission specifications, resulting in a smaller wing than the tractor configuration, the design of which was not iterated. A low wing arrangement was selected to allow the wing carry-through structure to pass under the cabin and to allow simple wing mounted landing gear. A T-tail arrangement was used to remove the horizontal tail from the turbulence of the fuselage and propwash, which can allow a small reduction in tail area and should allow attainment of NLF on the tail surface. A standard retractable tricycle landing gear arrangement was selected, with the nose gear retracting underneath the engine and the main gear retracting into the wing. Crosswind gear is also used for the tractor configuration. Cabin access is achieved by first stepping up onto the wing and then entering a side-hinged door located on the left side of the fuselage.

Unlike the pusher configuration, there was no practical place in the fuselage of the tractor configuration to mount the weather radar. Consequently, the radar was mounted in a pod on the left wing, similar in arrangement to that of the Cessna P-210 Centurion.

The cabin layout of the APT was sized by comparison with similar current GA airplanes, and the final layout is shown in Fig. 4. The cabin dimensions selected for the APT are relatively large compared to similar airplanes because current small GA airplanes are not known for cabin comfort. To improve marketability, the cabin of the APT was designed to ease this problem as much as practical, without causing undue weight or drag penalties. The fuselage cross section of the APT is shown in Fig. 5, and features a circular upper and a rounded square lower cross section. This arrangement was selected as a compromise between the structural efficiency of a fully circular cross section and the low wetted area and volume penalties of a fully square cross section. An illustration of a proposed APT cockpit layout is shown in Fig. 6. The layout features two sidestick controllers, one on each side of the cabin, and a center console containing the speed control handle. Due to the high degree of automation

Table of Geometry of the Tractor APT Configuration

| | Wing | Horiz. Tail | Vert. Tail |
|---|---|---|---|
| Area ($ft^2$) | 151.7 | 36.4 | 27.3 |
| Span (ft) | 42.7 | 12.8 | 5.6 |
| Aspect Ratio | 12.0 | 4.5 | 1.2 |
| Sweep Angle | -15°(@L.E.) | 9°(@L.E.) | 40°(@L.E.) |
| M.A.C. (ft) | 3.89 | 2.87 | 5.7 |
| Taper Ratio | 0.35 | 0.7 | 0.4 |
| Dihedral Angle | 3° | 0° | 90° |
| Incidence Angle | 1° | 0° | 0° |
| Twist Angle | 0° | 0° | 0° |
| Airfoil | Custom NLF Section | " | " |
| Thickness Ratio | 0.13 | 0.09 | 0.09 |
| Control Surf. Chord Ratio | 0.25 | 0.30 | 0.32 |
| Control Surf. Span Ratio | 0.72-1.00 | 0-0.98 | 0.20-0.85 |
| Flap Chord Ratio | 0.25 | N/A | N/A |
| Flap Span Ratio | 0.19-0.72 | N/A | N/A |

| | Cabin | Fuselage | Overall |
|---|---|---|---|
| Length (ft) | 11.17 | 29.33 | 34.75 |
| Max. Height (ft) | 4.67 | 5.42 | 9.92 |
| Max. Width (ft) | 4.58 | 4.92 | 43.40 |

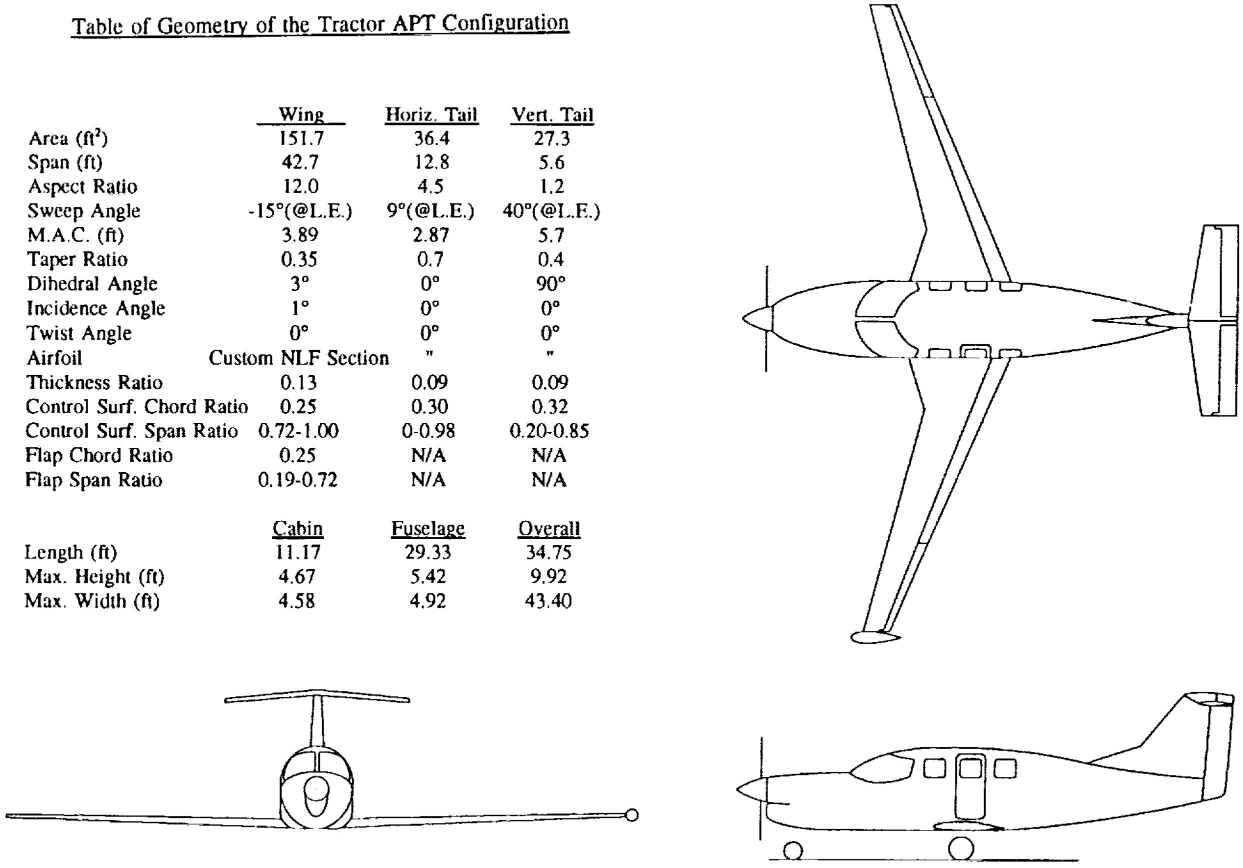

Fig. 3. Three-view of the APT tractor configuration.

in the flight control system, neither rudder pedals, brake pedals, flap handles, or landing gear handles are required(12). The layout features a HUD projected directly onto the windshield and a single LCD touch screen. The LCD will display all required systems information and will also be used for data entry; therefore, no other instruments or separate data entry devices are required in the cockpit. One interesting feature of this cockpit arrangement is that it allows incorporation of a sliding table or tray, which can be slid out from under the control panel to hold aeronautical charts, maps, or even drinks.

## 4. ADVANCED GUIDANCE AND DISPLAY

The overall objective of the navigation system was to reduce pilot workload. If possible, the pilot should not have to do anything except fly the airplane. A pilot workload study was conducted(2) to determine the workload a pilot must complete to make typical flights under two scenarios: the 1990 ATC system and the proposed IGG system. Each scenario included procedures for both VFR and IFR. From this study, it was estimated that at least a 30% reduction in pilot workload would be experienced due to the time saved from the capability of the IGG to monitor the navigation instruments. Additional workload reduction is possible because the pilot does not have to fly and communicate at the same time. Reductions are also expected since the pilot is no longer monitoring multiple instruments. Another objective was to be able to navigate vertically as well as horizontally with great accuracy using only onboard computers and positioning satellites. In this way, the onboard computer could build an approach into any airport even if no instrument approaches were established.

The GPS is a method of navigation using a constellation of satellites with known positions to calculate current position. Both the U.S. and the Soviet Union have been working individually on establishing a network of satellites. The NAVSTAR satellite system is the name given to the U.S. effort in global positioning. The system consists of 24 satellites, only 85% of which are presently in orbit. The constellation is expected to be completed by 1993. The satellites are grouped in six orbital planes with four satellites in each plane. Each satellite has a one-day ground track repeat, meaning that it will pass over the same spot once a day.

Each satellite contains almanac information about its orbit and position, and transmits it to the onboard receiver. Time delays measured in the signal are then used to calculate the distance from the satellite to the receiver. By tracking multiple satellites, the position of the airplane is triangulated from the known positions of the satellites. The satellites transmit two

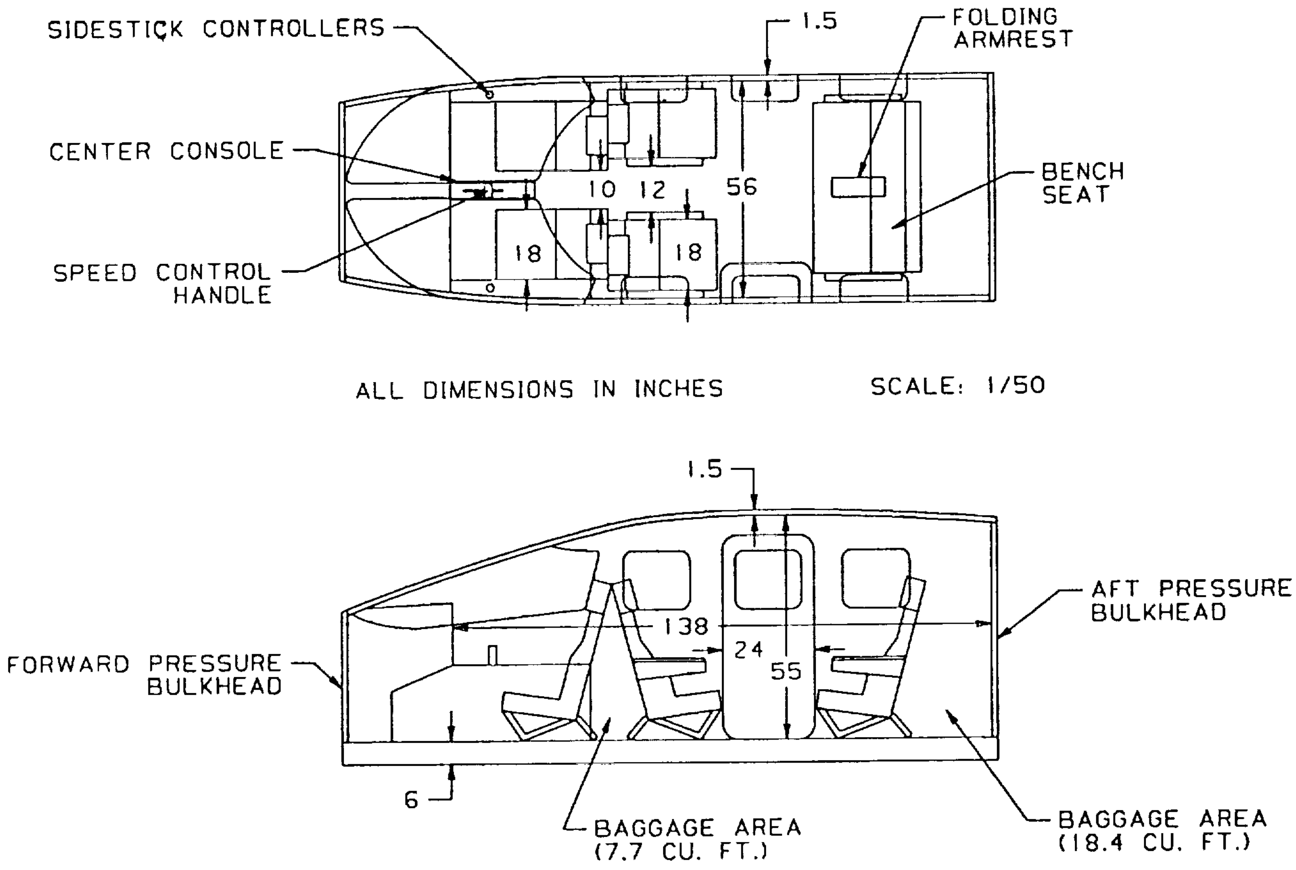

Fig. 4. Cabin layout of the APT.

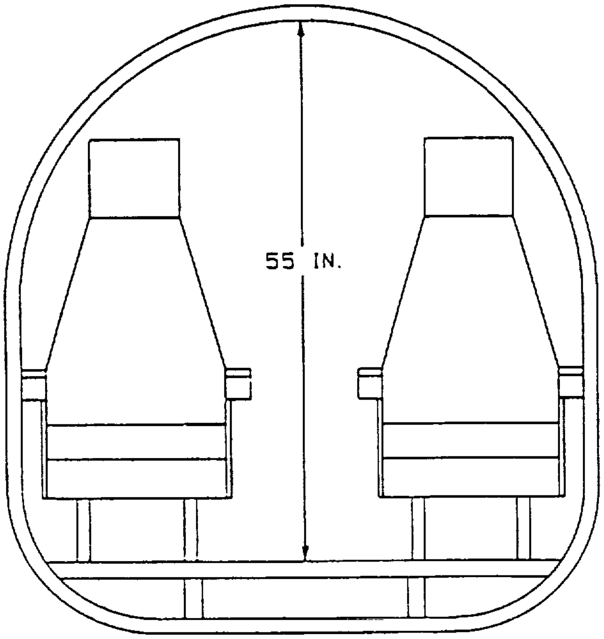

Fig. 5. APT cabin cross section.

codes. The P code has high accuracy and is encrypted and presently restricted to use by the military. A C/A code is available for civilian use, but its accuracy is limited to 50 m. The C/A code is simply a degraded form of the P code. The NAVSTAR system results in the ability to know longitude, latitude, and altitude at any given time.

Glonass represents the Soviet effort in global positioning. The main difference between the U.S. and Soviet systems is that Glonass is in a slightly lower orbit with an eight-day ground track repeat. The satellites are grouped into three orbital planes with eight satellites in each plane. This results in less consistent coverage over a given area. With NAVSTAR, there is a 10-hour period for which these eight satellites are in reception range for a given area. Satellite coverage can be expected over that area at the same time of day, every day, using only eight satellites. Even with 10 satellites, Glonass only repeats every eight days, resulting in inconsistent times of area coverage.

GPS can be used to update an INS to reduce the time-cumulative errors. GPS has the problem that the time delays used to calculate position result in a time lag. This means that the indicated position of the airplane is actually a few seconds behind the actual position. INS, however, can reduce this 12-second lag to instantaneous update rates resulting in higher position accuracy.

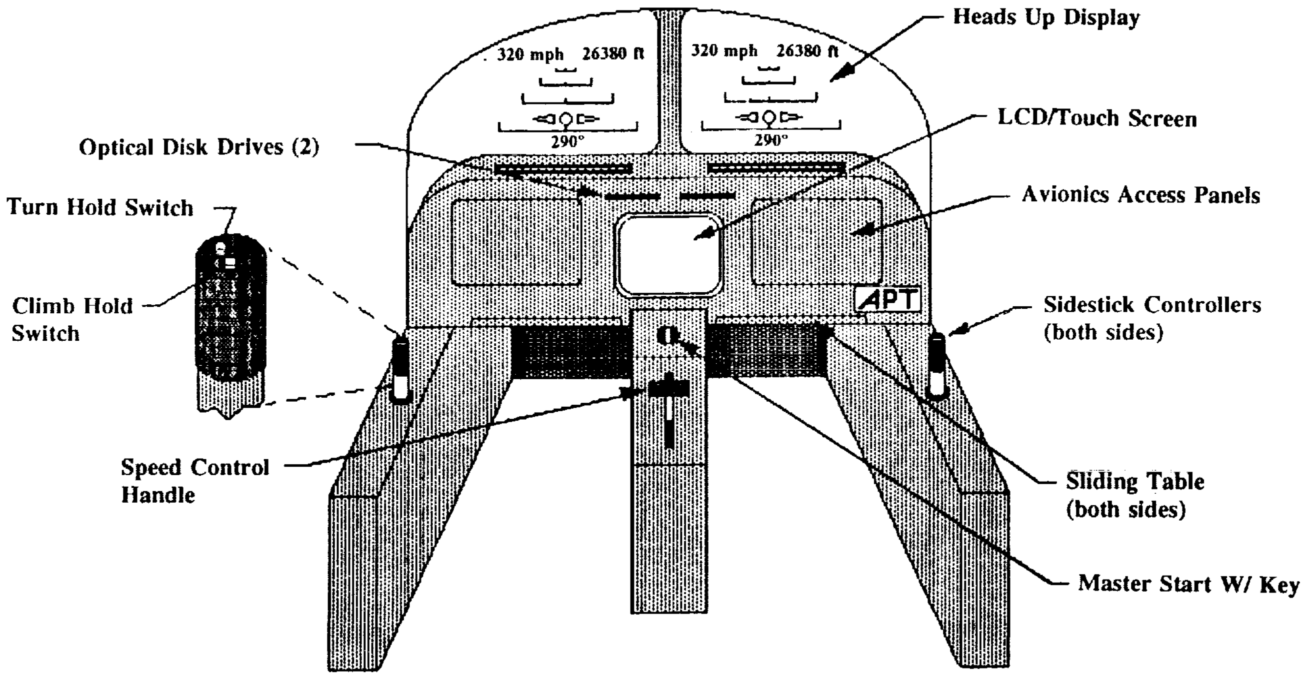

Fig. 6. Proposed cockpit layout of the APT.

The use of differential multichannel GPS receivers will increase the accuracy of the navigation system. By continuously tracking multiple satellites with multiple receivers, the efficiency of the updates is increased, and the noise in the signal and the power required to maintain lock on a satellite are reduced compared to a single receiver cycling through several satellites. The result of this when coupled with INS yields horizontal accuracies that will allow for zero visibility ground navigation and approach accuracies to satisfy CAT II approach criteria.

By the year 2000, advances in the NAS should allow for a GPS-equipped airplane to navigate point to point. It is doubtful, however, that they will allow an airplane without communications to enter controlled airspace. This depends on the advances made in the Data-Link system currently in use. Data-Link allows ATC to talk directly to onboard computers and to issue departure clearances. In the next 10 years, the system should be able to handle all traffic and routing information autonomously.

The only foreseen problem in the NAS is that automatic computer-generated approaches with CAT II criteria will not be allowed. To account for this by the certification date, an ILS system will have to be incorporated. It is believed, however, that GPS-based navigation will reach certification for en-route, DME, ADF, and VOR operations. The only unwanted addition to the APT instrumentation is a dual King KX-155 equivalent NAV/COM. This will not increase panel complexity. It can be worked in as an extra module and therefore does not increase pilot workload, only system complexity.

The complete navigation package will allow complete autonomous flight planning and management, with the exception of some communication requirements for traffic avoidance. It will allow point-to-point navigation with continuous flight information available to the pilot and will also allow CAT II approaches even into undeveloped fields where no approaches are established. The cost of the navigation system is estimated at $400,000.

The overall objective of the display system was to take a revolutionary look into possible improvements in cockpit instrumentation with an eye toward automation and user friendly operation. Ideally, the instrumentation and the display formats used in this cockpit should enable any pilot to fly this airplane under any weather conditions.

The advanced display system is composed of a map computer, DMUs, the DEU, a HUD, and a multifunction touch-screen display. The map computer is an optical disk-based system that handles all operating system functions, input processing, and the control of both the DEU and the multifunction display. The DEU provides the power, information, and control to the HUD.

The HUD, with the combiner integrated into the windscreen, performs two functions. It incorporates all flight-crucial information into the pilot's heads-up field of view. In this way, the pilot will never have to take his eyes off where he is flying to try and find an important piece of information from a cluttered instrument panel. By providing the pilot with a wide field-of-view display that can use pictorial representations of the outside world, the influences of spatial disorientation can be greatly reduced.

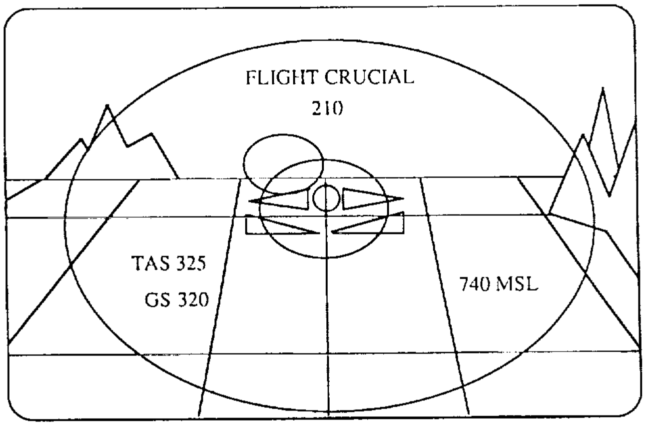

Fig. 7. Head-ups display in flight mode.

The multifunction/touch-screen display is used to display all non-flight-crucial information and for pilot interfacing. The multifunction display would be used for things such as flight planning/changes, monitoring of airplane systems and flight status, display of low priority Data-Link communications, etc. An example of what the HUD would display during flight is shown in Fig. 7. The price of the display system is estimated to be $600,000.

## 5. PROPULSION SYSTEM INTEGRATION AND PERFORMANCE EVALUATION

For reasons of efficiency throughout the flight envelope, a turboprop powerplant and propeller were selected as the propulsion system of the APT. Two Garrett TPE331-15 engines are connected to a single shaft through a Soloy twin-pac gearbox. These engines power a Hartzell HC-E5N-3L/L8218 propeller.

A survey of several manufacturers was conducted to determine a pool of propeller candidates that may be used on the APT. The five-bladed Hartzell HC-E5N-3L/L8218 was selected from this pool as the propeller for the APT. Due to the large power plant, the Hartzell HC-E5N-3L/L8218 was not able to accept all the power available at its original diameter. To keep the propeller tip Mach number at an acceptable level, the rotational speed had to be decreased from 1885 to 1687 RPM, and the diameter was increased from 85 to 95 in. The designers of the HC-E5N-3L/L8218 specifically designed the blades to operate in a range where tip Mach numbers reached 1.0. The tips of the HC-E5N-3L/L8218 use the most advanced transonic airfoil cross-sections. Three-dimensional effects are taken into account for precise tailoring of blade twist. As a result, the manufacturer claims that the tips are lightly loaded and fly at less than 2° angle of attack at this flight condition. Therefore, the transonic losses are 75% to 90% lower than a traditionally designed blade.

The power plant and propeller installation for the pusher configuration is shown in Figs. 8 and 9. A small shaft extension, which does not appear on the tractor configuration, was added to the gearbox of the pusher configuration to allow better faring of the aft end of the aircraft. To reduce ducting losses, short inlet ducts with gradual bends were used. Both engines are supported by one very rigid support truss to minimize gearing mismatch at the engine power takeoff shaft. For maximum accessibility, it was determined that the truss should have hinged members that would swing up and out when a certain engine accessory needs to be replaced or receive maintenance. An oil cooler is incorporated to improve reliability and lower maintenance. Firewalls and a fire suppression system have been included for safety, and chip count sensors were included for prognostics/diagnostics. Torque, RPM, and fuel flow instruments are integrated into the onboard computer for system monitoring.

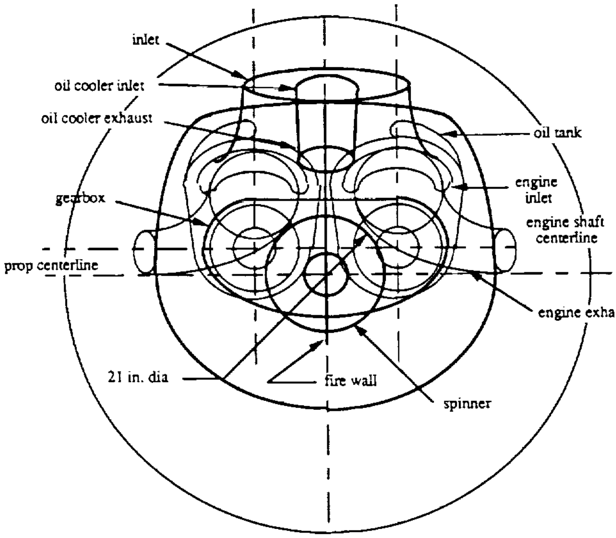

Fig. 8. Front view of the propulsion system integration for the APT pusher.

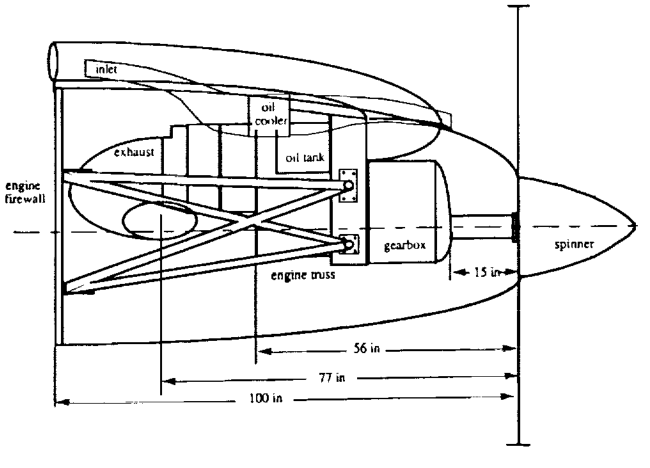

Fig. 9. Side view of the propulsion system integration of the APT pusher.

## 6. AIRFOIL DESIGN

The airfoil, designated as HSNLF-3012, is designed for a cruise Mach number of 0.73 at a Reynolds number of $5 \times 10^6$. The HSNLF denotes "High Speed Natural Laminar Flow" and the 3012 denotes a cruise lift coefficient of 0.30 and thickness ratio of 12% chord. At these conditions, approximately 60-70% laminar flow boundary layers are expected on the upper and lower surfaces. In addition, a maximum lift coefficient of 1.4 at a Mach number of 0.1 and Reynolds number of 2 million is a design condition.

The HSNLF(1)-0213 airfoil was used as a basis for the design. Because the HSNLF(1)-0213 airfoil drag-rise Mach number is too low for the APT design cruise speed conditions, some modifications had to be made. The drag rise Mach number was increased by decreasing the thickness ratio of the airfoil and by giving the wing sweep. After scaling down the HSNLF(1)-0213 and reshaping the airfoil afterbody, the desired conditions were met. The airfoil maintains natural laminar flow on 58% and 70% of the upper and lower surfaces respectively.

## 7. WEIGHT AND BALANCE

The component weights and the aircraft balance were determined(28). Table 2 lists the results of the weight estimations. The weights for the pusher configuration are higher because it was resized in Phase II design to meet the mission specifications.

The center of gravity travel is 9 in (20 % of the wing MAC) for the tractor configuration and 7 in (15% of the wing MAC) for the pusher configuration. Typical c.g. ranges for similar aircraft are 8-16 inches and 10-21% of the wing MAC(29). This indicates that the results for the APT are reasonable.

## 8. STABILITY AND CONTROL

The stability and control derivatives for both APT configurations were estimated for three flight conditions (power approach, climb, and cruise)(30). Both configurations were determined to be trimmable in all three flight conditions investigated.

It is important to the pilot that certain modes of motion of the airplane are well behaved. The longitudinal and lateral-directional mode shape characteristics of both configurations were calculated(30) for the same three flight conditions used in calculating the stability and control derivatives. The tractor configuration satisfies level 1 flight requirements in the phugoid mode in all three flight conditions. The pusher, however, has slightly low damping ratios in both cruise conditions. Both configurations satisfy level 1 short-period flight requirements for all three flight conditions. The spiral mode requirements for level 1 flight are satisfied for both configurations, but the spiral mode is too stable in all three conditions for the tractor and in power approach for the pusher. Decreasing the wing dihedral will alleviate this. Both configurations satisfy the requirements for level 1 dutch roll flying qualities except for the pusher configuration in both cruise conditions. This can also be corrected by changing the wing dihedral or the size of the vertical tail. Both configurations satisfy the roll requirements for level 1 flying qualities in all three flight conditions.

## 9. STRUCTURAL CONSIDERATIONS

The wing and fuselage structural layouts and manufacturing processes were determined for the pusher configuration. The fuselage skin is to be made of Glare 3, the upper wing skin of 7075 aluminum, and the lower wing skin of 2024 aluminum.

TABLE 2. Comparison of the APT with the competition.

| | APT Pusher | APT Tractor | Socata/Mooney TBM-700 | Beech Starship | Piaggio P-180 |
|---|---|---|---|---|---|
| *Weights* | 7,264 | 6,247 | 6,510 | 14,400 | 10,510 |
| Maximum Takeoff weight (lb) | | | | | |
| Standard empty weight (lb) | 4,311 | 3,661 | 3,637 | 10,320 | 6,700 |
| Maximum useful load (lb) | 2,800 | 2,800 | 2,646 | 4,280 | 3,810 |
| Maximum wing loading (psf) | 55.9 | 41.2 | 32.2 | 51.3 | 61.95 |
| *Performance* | 1,961 | 2,050 | 1,936 | 3,280 | 2,415 |
| T.O. Fieldlength (ft) [sls,isa] | | | | | |
| Maximum climb rate (fpm) | 4,000 | 4,650 | 2,380 | 3,100 | 3,650 |
| Best climb rate speed (kt) | 260 | 243 | 123 | 180 | 160 |
| Clean stall speed (kt) | 76 | 77 | 75 | 99 | 105 |
| Landing stall speed (kt) | 60 | 63 | 61 | 84 | 82 |
| Service ceiling (ft) | 45,000 | 44,000 | 30,000 | 41,000 | 41,000 |
| Normal cruise speed (kt) | 310 | 300 | 282 | 270 | 320 |
| at altitude of (ft) | 40,000 | 44,000 | 30,000 | 35,000 | 41,000 |
| High speed cruise (kt) | 415 | 350 | 300 | 335 | 400 |
| at altitude of (ft) | 20,000 | 25,000 | 26,000 | 22,000 | 27,000 |
| Fuel flow for: | 323 | 330 | 312 | — | 460 |
| Normal cruise (lb/hr) | | | | | |
| High speed cruise (lb/hr) | 708 | 700 | 320 | 984 | 860 |
| Maximum range (nm) | 1,300 | 930 | 1,000 | 1,450 | 1,800 |

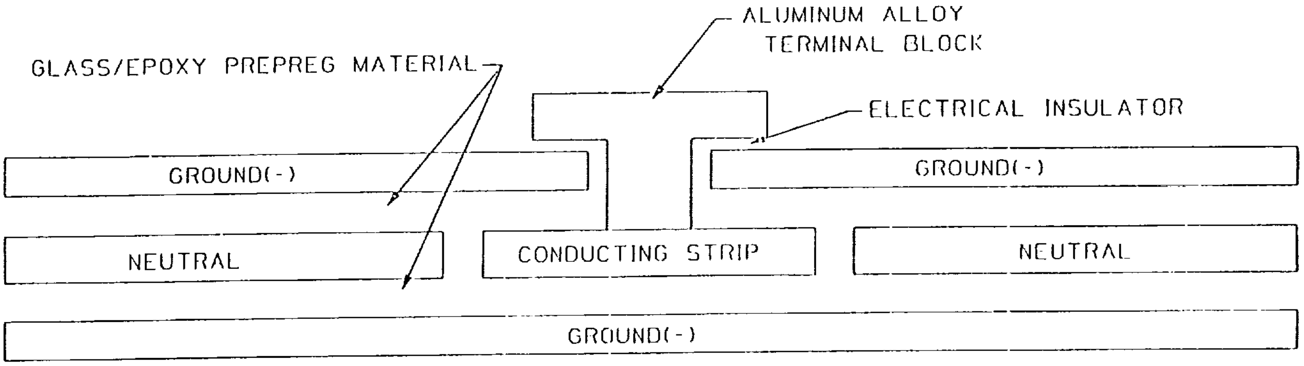

Fig. 10. Smart structure power bus and tap configuration.

The supporting structures of both components will be made of conventional aluminum alloys. Both the wing and the pressurized section of the fuselage were analyzed with a finite structural element program to size the structural members. Outside-in tooling methods will be used to improve surface smoothness of the components to allow for the attainment of natural laminar flow. Skin splices and surface waviness and gaps will be within required levels(31) to maintain natural laminar flow.

The APT will incorporate the use of smart structures. The use of embedded sensors in a laminate material can play four key functions: monitoring of the manufacturing process, allowing nondestructive evaluation of each individual structure at any point in the manufacturing or assembly process, vehicle health monitoring, and complementing the flight control system.

Optical fibers will be used for data transmission to take advantage of their immunity from electromagnetic interference and also to take advantage of the savings in weight (about 4%) and volume over conventional copper wire bundles. Optical fiber sensors will be incorporated into the aircraft using the smart-skin approach primarily for vehicle health monitoring. Power transmission by optical fiber will only be considered an option for low power (3 W or less) applications such as simple electronic circuits and active sensors. Optical fibers intended for sensing applications will be standard fiberoptic glass. Optical fibers intended for data transmission will be of the polycarbonate type because of the simpler connection systems and the ease of repair associated with this type of fiber. Optical fibers to be used for data transmission will be too thick to be embedded in the Glare laminate regardless of the type of fiber used, and will therefore be attached to the inner surface of the Glare panels.

Coatings for the fiberoptic cables were selected to ensure protection from the heat generated during the manufacturing of the laminate and the strain from dynamic loadings during flight. It was determined that optical fibers used for data transmission will be coated with acrylate to protect and insulate them from shock and stress, and optical fibers intended for sensing applications will be coated with Polyaimide B, a thermoset material.

The possibility of using aluminum alloy strips, integrated into one or more of the aluminum layers of the Glare laminate, as power busses was also investigated. This would allow the electrical bus to be used as a structural member and could lead to a substantial weight savings. A schematic of this concept is shown in Fig. 10. The feasibility of this concept is yet to be verified and warrants further research. A major concern is the repairability and redundancy requirements of such a system. The imbedded strips would make it difficult to repair. The solution accepted at this time is to have triply redundant busses. If an area is damaged, it would be repaired only structurally. The damaged power bus would be "turned off" and the system would simply tap into one of the backup strips.

## 10. SYSTEMS

The layout of the major systems of the APT was designed for both configurations. These systems include the pressurization, pneumatic, air conditioning, oxygen, fuel, de-ice, escape, avionics, electrical, and primary flight control systems. A specialized electro-impulse de-icing system was designed to accommodate maintenance concerns without depreciating the amount of obtainable laminar flow. Detailed analyses were also conducted on the electrical and primary flight control systems. All system conflicts that have been identified have been corrected.

Trade studies were conducted on rate command, attitude command, and decoupled response command flight control systems. A decoupled response control system was selected for the APT because it offers advantages over the rate and attitude command systems. A decoupled response control system significantly reduces pilot workload and improves the handling qualities over conventional rate command systems, especially during low-visibility IFR flight conditions. It has the potential to make flying an airplane as easy and safe as driving a car. The system is particularly well suited for operation by novice and infrequent pilots, though it is also easily adapted to by experienced pilots. Each primary response variable of the airplane is a function of only one cockpit control position, which provides intuitive and easy-to-learn operation. The system automatically compensates for speed and trim changes due to flap

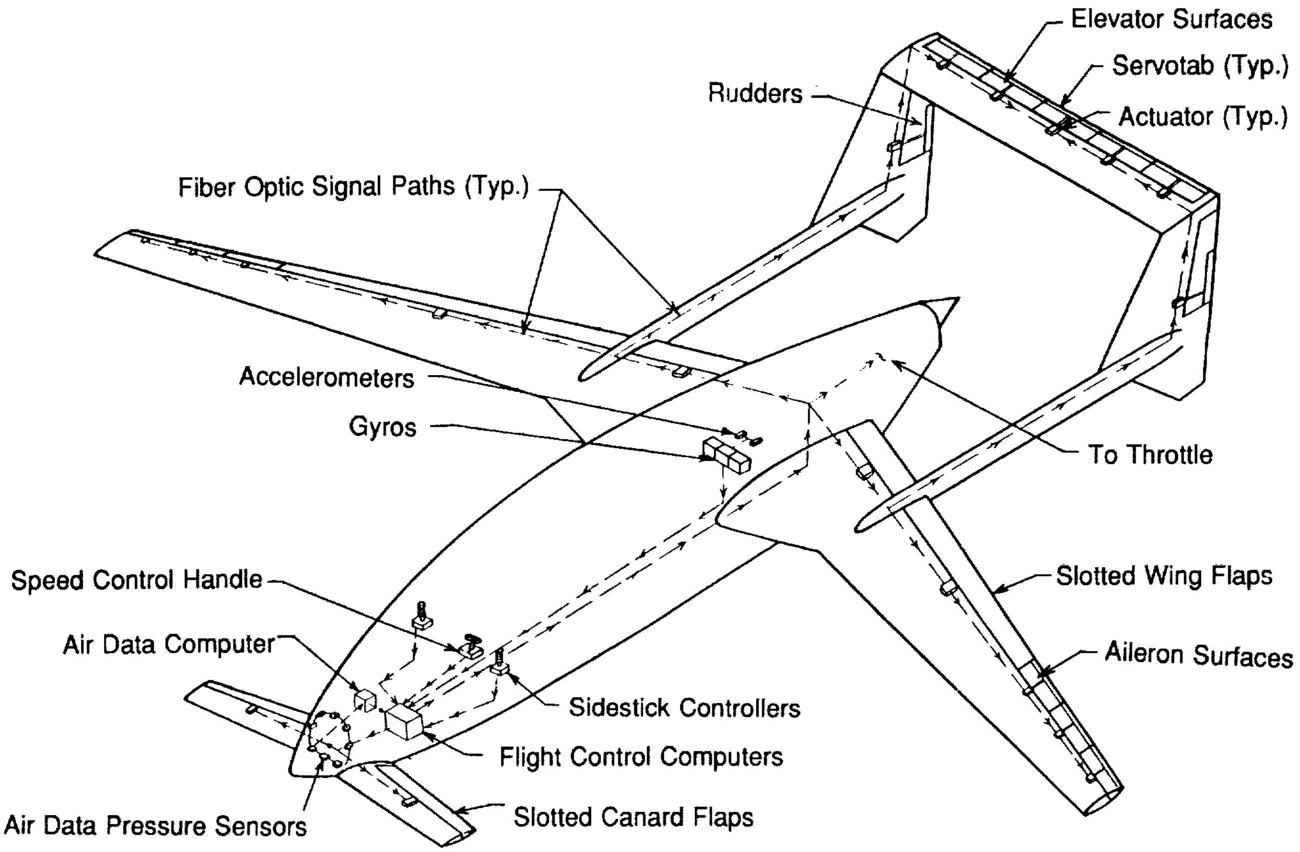

Fig. 11. Preliminary flight control system layout.

deflection, landing gear extension, and steep turns. This considerably decreases pilot workload, especially during approach and balked landing flight conditions. The system makes the type and sign of the steady-state airplane responses the same as those of the initial response, again providing intuitive operation. The system automatically damps out the annoying phugoid oscillation.

Trade studies were also conducted for several flight control system arrangements: reversible mechanical, reversible mechanical with SSSA, and irreversible fly-by-wire/fly-by-light (FBW/FBL). Due to the importance of providing enhanced flying qualities to the APT project, the mechanical reversible system was immediately eliminated from consideration since it did not allow practical stability augmentation. In general, the results showed that the SSSA system should be less expensive to develop, build, and certify, more reliable due to the mechanical primary controls, and easier to certify due to the extensive database of similar airplanes and the relative simplicity of the system. The irreversible FBL system was, in general, the higher performance system since it gives much better handling qualities, allows the safety of flight envelope protection, potentially weighs less, and reduces pilot workload and training requirements. It was apparent that if the cost, reliability, and certification problems of FBL could be overcome, it was the best choice for the flight control system of the APT. Considering recent technological advances in areas such as microprocessors, fiberoptics, and electromechanical actuators, it seems likely that by the time of certification of the APT in 1999 these problems can be practically overcome(32). As a result, an irreversible FBL control system was selected for the APT (Fig. 11).

Several control surface/actuator arrangements were investigated for the APT flight control system. A multiple-segment control surface arrangement was selected to provide redundancy in the case of actuator failure, using the following segment numbers: seven aileron segments (per aileron), five elevator segments, and two rudder segments (one on each vertical tail). One of the primary advantages of this multiple surface arrangement is that it was designed to provide a constant actuation force for all control surfaces. Hence, one common actuator can be used for all control surfaces, which should provide significant cost and maintenance advantages. Servotab actuation of the control surfaces was selected to allow use of a smaller actuator (for the same control power), which provides the advantage that the actuators should be lighter, less expensive, and have smaller power requirements.

An iron bird has been built and tested. The iron bird involved a simulation of an aileron-tab configuration for lateral control, an investigation to see if a servotab can be used to control

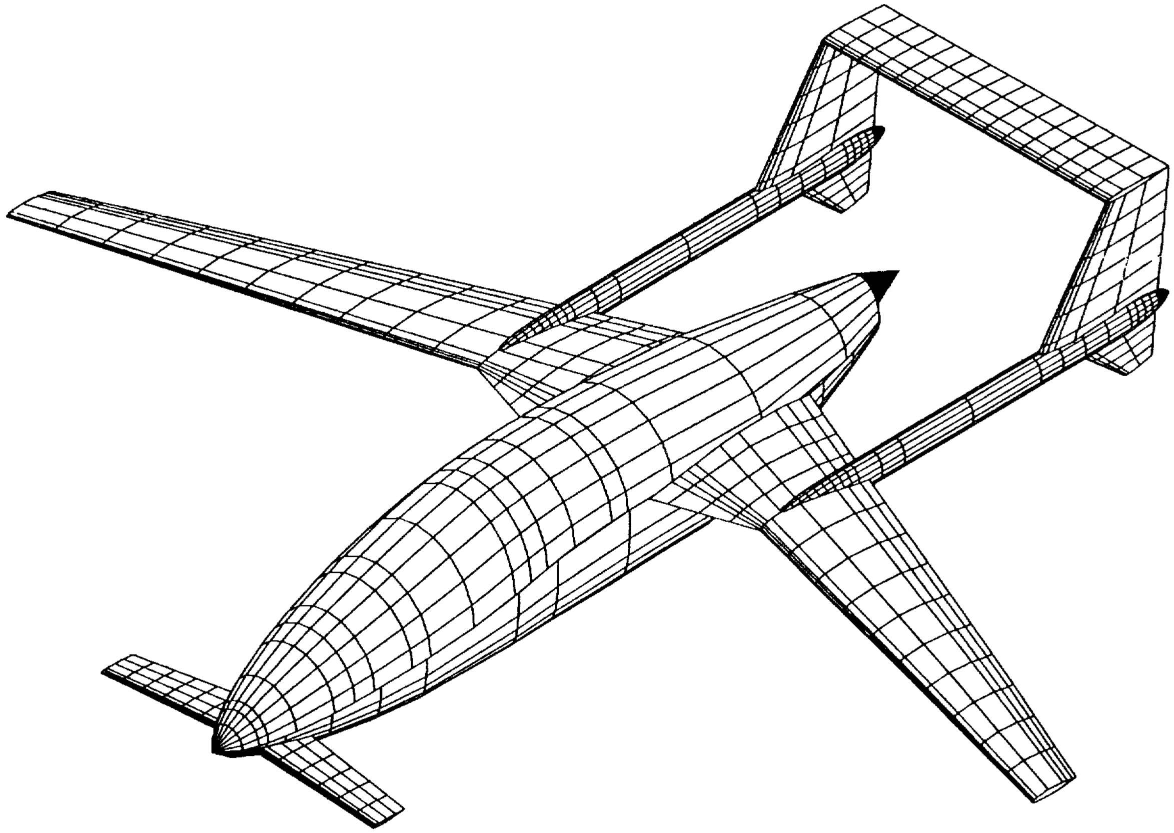

Fig. 12. 3D ACAD model of the APT Pusher configuration.

the aileron surface. The advantage of this configuration is the elimination of the heavy and costly actuators needed to control the ailerons.

Trade studies were conducted between electrical signal paths (FBW) and fiberoptic signal paths (FBL). A FBL arrangement was selected primarily because fiberoptic signals are inherently immune to environmental effects such as EMI, HERF, and lightning strikes. Fiberoptic cables are also lighter than equivalent electrical cables(18).

To enhance the safety of the APT, a flight envelope protection system will be incorporated. This system will feature protection of the following variables: airspeed, angle of attack, load factor, pitch attitude angle, and bank angle. Such a system can greatly enhance safety by preventing beginning and infrequent pilots from placing the airplane into an unsafe attitude, and by giving the pilot quick and positive access to the entire flight envelope of the airplane.

Due to the FBL control system, the need for large, bulky center-mounted control columns has been eliminated. Experience with civil aircraft such as the Airbus A320, the Rutan Long-Eze, and the new Lancair IV has shown that sidestick controllers provide an unobstructed view of the cockpit panel and allow much easier access to the cockpit. The sidestick controller allows a more comfortable cockpit layout for the pilots and provides more flexibility in flight deck arrangement. Perhaps the most important advantage of sidesticks is that pilots simply tend to like flying with them. The APT cockpit layout will thus feature sidestick controllers, with one provided on each side of the cabin. Two switches located on the top of each sidestick will be provided to command climb hold and turn hold functions. A single-speed control handle is mounted on the center console of the cockpit, where it is accessible to both pilots. The speed control will be used to command speed both on the ground and in flight, and functions in a manner similar to the cruise control of an automobile. Due to the extensive flight envelope protection used in the APT flight control system, artificial feel units on the sidestick controllers should not be required. Experience with the Airbus A320 has shown that simple linear springs in the controller work well, and also provide the pilot with a more comfortable interface than if an artificial feel unit were employed.

## 11. PERFORMANCE AND COST

The performance capabilities of both configurations of the APT are shown in Table 2. Table 2 also compares the APT configurations with the primary competitors: the Piaggio P-180, the TBM-700, and the Beech Starship. The pusher configuration

TABLE 3. Project cost estimates for the APT aircraft (pusher configuration)

| Year 2000 dollars, 200 aircraft with 20-year service life | |
|---|---|
| RDTE Cost | 62.7 million |
| ACQ Cost | 641 million |
| OPS Cost | 6.87 billion |
| DISP Cost | 76.5 million |
| LCC | 7.65 billion |
| AEP | 3.516 million |

meets all the requirements defined in the mission specification. This required the resizing of the entire aircraft. The APT configurations compare favorably with the competitors in Table 2.

Table 3 contains the breakdown of the estimated total APT project costs. These cost estimates are based on year 2000 dollars, with a production run of 200 aircraft, with a service life of 20 years, and were determined by the methods of reference 33.

## 12. CONCLUSIONS

Phases I and II of the preliminary design of an advanced GA aircraft have been completed. It was determined that an IGG-equipped airplane can lead to a 70% reduction in pilot workload. Also, using differential GPS/INS interface, CAT II approaches and zero-visibility ground operations are possible. Through the use of a heads-up display unit and a multifunction touchscreen display, all other flight instrumentation can be excluded.

Glare is planned for the skins of the APT fuselage and conventional aluminum will be used for the wing skins. Outside-in tooling methods will be used in the manufacturing processes of the APT to achieve the smooth surfaces required to maintain natural laminar flow. Electrical power is to be distributed by a triple-redundant, embedded power bus system. Further research needs to be done regarding the design and special manufacturing requirements of an embedded power bus system.

The APT will have a FBW, decoupled response flight control system that will provide control system operations that should greatly improve flying qualities. The pusher design was iterated in Phase II to meet all the performance requirements (Fig. 12).

## REFERENCES

1. Burgstahler, Huffman, Ryan, *Market Survey Report for the Advanced Personal Transport,* The University of Kansas, 11 September 1990.
2. Axmann, Knipp, Roper, Wenninger, *Pilot Work Load Study,* The University of Kansas, 20 September 1990.
3. Hoffmann, Rodkey, Roper, *Advanced Guidance and Display Study,* The University of Kansas, 30 November 1990.
4. Axmann, Knipp, *Equipment List for Typical Aircraft and Proposed APT,* The University of Kansas, 4 October 1990.
5. Burgstahler, Huffman, *Mission Specification for the Advanced Personal Transport,* The University of Kansas, 20 September 1990.
6. Barrett et al., *Preliminary Design of Two Configurations,* The University of Kansas, 15 December 1990.
7. Anderson, Jackson, *Loads Analysis of the Advanced Personal Transport,* The University of Kansas, 4 December 1990.
8. Chronister, Jackson, *Fuselage Design and Manufacturing Study,* The University of Kansas, 4 December 1990.
9. Bauguess, Weiss, *Wing Layout, Design and Manufacturing Tolerances of the Advanced Personal Transport,* The University of Kansas, 12 December 1990.
10. Hoffmann, Wu, *Electrical System Design Considerations for the Advanced Personal Transport,* The University of Kansas, 20 November 1990.
11. Dreiling, Weiss, *Results of Investigation into the Use of Smart Structures for the Advanced Personal Transport,* The University of Kansas, 4 December 1990.
12. Shumate, Woolpert, *Primary Flight Control System Study,* The University of Kansas, December 1990.
13. Axmann, Knipp, *System Layouts for the Advanced Personal Transport,* The University of Kansas, 30 November 1990.
14. Bauguess, Lawson, Woolpert, *Maintenance and Repairability Study,* The University of Kansas, 13 November 1990.
15. Dirkzwager, Schlatter, *Natural Laminar Flow Airfoil Design for the Advanced Personal Transport,* The University of Kansas, 9 November 1990.
16. Barrett, Chronister, *Design, Construction, and Test of the Iron Bird,* The University of Kansas, 11 December 1990.
17. Gomer, Roskam, *Design Developments for Advanced General Aviation Aircraft,* SAE Technical Paper 911022.
18. Evans, DeMoss, *Electrical System Report for the Advanced Personal Transport,* The University of Kansas, April 1991.
19. Knipp, Dirkzwager, *Manufacturing Plan and Cost Analysis for the Advanced Personal Transport Pusher Configuration,* The University of Kansas, May 1991.
20. Dirkzwager, *Structural Design of the Advanced Personal Transport Pusher Configuration,* The University of Kansas, May 1991.
21. Knipp, Keiter, Demoss, *Advanced Guidance and Display Study for the Advanced Personal Transport,* The University of Kansas, April 1991.
22. Barrett et al., *Design, Construction, Test and Evaluation of an Aileron-Servotab Iron Bird,* The University of Kansas, May 1991.
23. Barrett et al., *Preliminary Airframe Design for the Advanced Personal Transport Pusher Configuration,* The University of Kansas, May 1991.
24. Barrett et al., *Primary Flight Control System Design Considerations for the Advanced Personal Transport,* The University of Kansas, May 1991.
25. Evans, Smith, Wenninger, *Maintenance and Repairability Study for the Advanced Personal Transport,* The University of Kansas, May 1991.
26. Kendall, *The Minimum Induced Drag, Longitudinal Trim and Static Longitudinal Stability of Two-Surface and Three-Surface Airplanes,* AIAA Report 84-2164.
27. Selberg, *Analytical Study of Three-Surface Lifting Systems,* NASA TN 850866.
28. Roskam, *Airplane Design Part V: Component Weight Estimation,* Roskam Aviation and Engineering Corporation, Ottawa, KS, 1989.
29. Roskam, *Airplane Design Part II: Preliminary Configuration Design and Integration of the Propulsion System,* Roskam Aviation and Engineering Corporation, Ottawa, KS, 1989.
30. Roskam et al., *Advanced Airplane Analysis Program (AAA),* The University of Kansas.
31. Holmes, *Manufacturing Tolerances for Natural Laminar Flow Airframe Surfaces,* AIAA Paper 85063.
32. Tucker, "Advances in Flying Control System", from the conference *Civil Avionics - The Future International Scene,* Royal Aeronautical Society, London.
33. Roskam, *Airplane Design Part VIII: Airplane Cost Estimation: Design, Development, Manufacturing, and Operating,* Roskam Aviation and Engineering Corporation, Ottawa, KS, 1989.