Flight Plan Management with George Jetson as Pilot

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Abstract

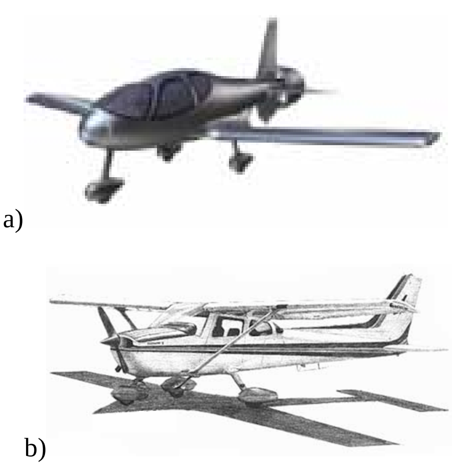
We are developing an aircraft Flight Plan Manager (FPM) that incorporates a variable autonomy plan repair algorithm and provides real-time trajectory adaptation in response to both performance degradation and traffic and weather conflicts. FPM reduces environmental impact, improves safety, and simplifies personal air vehicle (PAV) operation by coupling realistic performance and noise models with intuitive pilot interfaces and robust optimization algorithms. Enhanced situational awareness and detailed procedural guidance improve safety and reduce reliance on specialized pilot knowledge. Reuse of existing navigation and autopilot systems will minimize production cost. Our long-term goal is to develop and validate the models and methods that will make FPM part of every PAV cockpit.

Introduction

The Personal Air Vehicle (PAV) has been proposed to make flight a convenient and accessible transportation alternative for short to medium range travel. For PAVs to become commonplace, however, a low-cost, reliable vehicle must be developed. Similarly low-cost flight control avionics and software must enable levels of safety and robustness to pilot error (inexperience) comparable to those enjoyed by existing automobiles. Given that PAVs will inevitably operate in close proximity to residential neighborhoods, environmental impact (noise) must also be minimized via quiet aircraft technology and flight trajectories that minimize noise radiated to populated regions when flying at low altitudes.

Exciting new PAV technologies and products will revolutionize the General Aviation (GA) community. As shown in Figure 1a, one PAV concept utilizes standard lifting surfaces but with alternate quiet propulsion technology. The pictured "Tailfan" design is powered by an automotive V-8 engine designed to provide a 500-mile, 200-mph cruise speed for the five-passenger PAV. In comparison, the popular Cessna 172 (C-172) shown in Figure 1b carries four passengers and, depending on engine and fuel tank configuration, provides on average a 500-mile, 130-mph cruise speed at significantly higher noise. Fortunately, the performance models for the new PAV class will be similar to their GA counterparts, so that avionics systems currently available for GA aircraft can be straightforwardly adapted for the PAV.

Our Flight Plan Management (FPM) system enables a low-time PAV pilot to safely manage PAV flight operations during normal and exceptional situations. Illustrated in Figure 2, the FPM executes in three modes: (1) Flight Planning, (2) Flight Plan Monitoring and Execution, and (3) Real-time Flight Plan Adaptation/Repair. During preflight preparation, the pilot and FPM collaboratively construct flight plans (Mode 1) that follow user-preferred routing constraints (waypoints), optimize overall performance, and minimize radiated ground noise (sound exposure level (SEL)). During execution (Mode 2), the flight plan and nearby traffic and weather events are continuously monitored. Anomalous events are reported to the pilot and prompt in-flight plan adaptation (Mode 3). Response deadlines for events such as traffic conflicts or in-flight emergencies (e.g., engine failure) are computed to enable real-time response. Suggested adaptation strategies in the form of prioritized feasible landing sites and trajectories to those sites are provided within a variable autonomy interface.



a)

b)

Figure 1: The NASA Langley PAV and the Cessna 172.

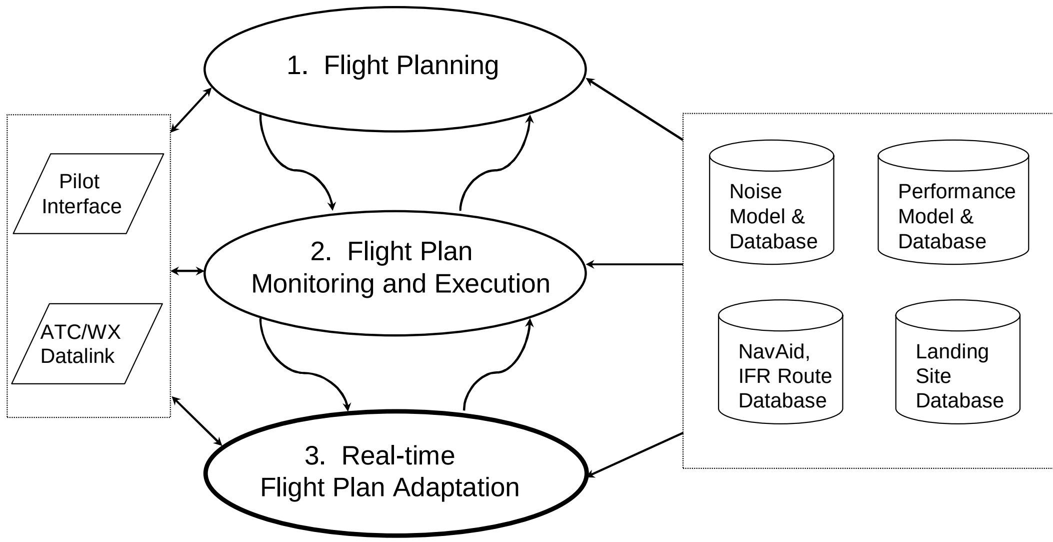


Figure 2: Flight Plan Management Modes and Interfaces.

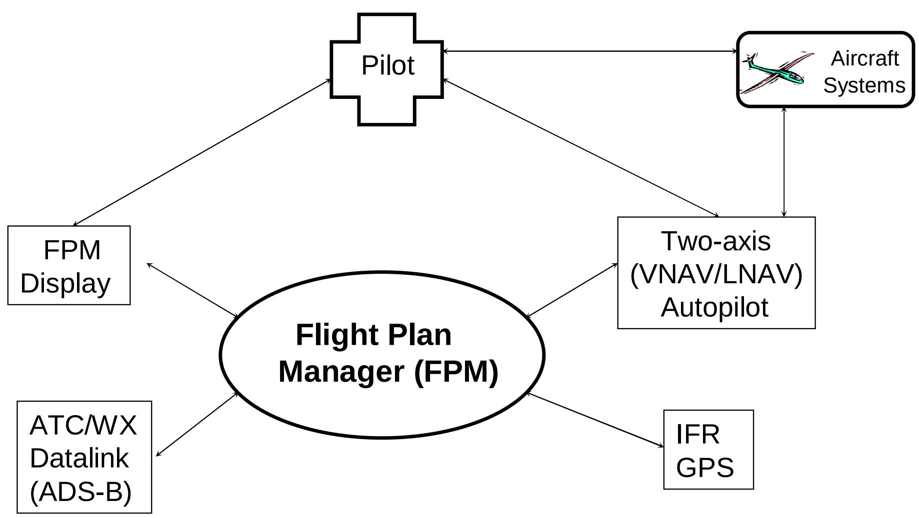


Figure 3: FPM Avionics Interface.

To successfully guide the pilot through all flight planning and monitoring processes, the FPM must incorporate a variety of models and data to provide efficient, optimized flight plans and robust (safe) operations during anomalous high-workload situations. Components are adapted from existing GA products when possible to allow fundamental research efforts to be directed toward the development and integration of emerging noise prediction and in-flight plan adaptation technologies into the FPM architecture. As shown in Figure 3, the FPM will be linked to existing autopilot and GPS units, and will evolve to accommodate air traffic control (ATC) and weather (WX) datalink capabilities as they are made available at reasonable cost. The pilot interface to the FPM is based on handheld computing technology (a laptop or pen PC in future work). Graphical displays will provide basic data analogous to that provided in flight management system (FMS) computer display unit (CDU) and navigation display (ND), augmented by FPM-specific data that has no FMS counterpart.

Development of Models and Methods

The Flight Plan Manager (FPM) is a low-cost software architecture designed for ease-of-use and safe, robust flight operations. Coupled with efficient performance and noise models, the high-level FPM software architecture supports multi-objective plan optimization and provides robust in-flight adaptation capabilities. Fundamental research (in progress) is focusing on the development and integration of noise and performance models into a laptop-based software prototype, using a Cessna 172 as the performance and noise model reference. The FPM prototype will be evaluated in all modes of operation in simulation and in an actual Cessna 172 cockpit to refine the software and algorithms and to identify additional R&D necessary to actually produce a viable commercial product.

FPM Architecture

As shown above in Figure 2, the FPM switches between three modes: (1) flight planning, (2) flight plan monitoring and execution, and (3) real-time flight plan adaptation. The following algorithms provide an overview of FPM operations, including conditions under which the pilot or FPM will activate a different mode of operation.

Mode 1: Flight planning

1. Pilot enters departure/destination airport identifiers.
2. Pilot enters any "user-preferred" waypoints via keypad navigation identifiers or on a multi-resolution map.
3. Pilot adjusts weighting factors (default values available) for optimization over noise and time/fuel. The tradeoff between noise reduction and safety constraints (e.g., how steep can the approach be flown?) will be driven by PAV performance characteristics, autopilot capabilities, and level of pilot experience.
4. FPM computes and displays a route that complies with pilot input given wind/weather/traffic advisories. Such advisories enable conflict analysis and may affect the location of optimized waypoints (e.g., propeller noise is a function of both steady wind and gusts).
5. Pilot examines the route from a series of displays generated by the FPM: a) multi-resolution map showing waypoints and route segments, b) standard flight plan table showing waypoint identifiers and landmarks, and c) noise contour plots for low-altitude route segments near noise sensitive areas.
6. Pilot has the following options: a) accept flight plan, b) make minor route adjustments by moving individual waypoints or entering alternative trim settings (airspeed, bank for turns, etc.), c) return to Step 2 for major changes.
7. FPM validates an accepted flight plan against performance, noise, fuel, and airspace constraints. FPM transmits data for the validated flight plan to ATC and stores the plan for in-flight monitoring and execution.
8. Pilot switches to *FPM Mode 2*, flight plan monitoring/execution.

Mode 2: Flight plan monitoring and execution

1. FPM computes current aircraft state from autopilot and GPS navigation/wind data and autopilot output commands.
2. FPM verifies that current state is consistent with expected state based on performance model and aircraft control surface and [expected] throttle configuration. For low-cost two-axis autopilots, FPM recommends throttle settings and highlights the throttle display when adjustment is required to follow the executing flight plan.
3. If current state deviates significantly from expected state, FPM notifies pilot of the deviation. By default, FPM continues executing the current plan in the background and activates *FPM Mode 3* to adapt the flight plan.
4. If potential traffic and/or weather conflicts are detected, FPM notifies pilot. By default, FPM continues executing the current plan in the background and activates *FPM Mode 3* to adapt the flight plan.
5. Return to Step 1.

Mode 3: Real-time flight plan adaptation

1. FPM computes real-time deadline for plan adaptation activity based on proximity to the airborne conflict (traffic/weather) or degradation of landing footprint (reachable landing sites) over time. This deadline is not defined (infinite) if the pilot manually activated Mode 3 and the executing plan is valid.
2. If responding to a situation in which aircraft performance is degraded, the FPM (in the background) ranks emergency landing sites and develops a feasible trajectory to the highest-priority site.[1]

[1] The comprehensive identification of reduced performance capabilities is a formidable task and remains an area of active research. The FPM will be architecturally capable of accommodating this capability, and in parallel research efforts we are building a trim database to define valid flight states for a variety of in-flight failures (e.g., total loss of thrust, jammed control surfaces).

3. If responding to a conflict alert, FPM (in the background) computes avoidance maneuver(s) and downstream intercept of original flight plan, adopting a real-time plan repair strategy.
4. If the planning deadline is tight, FPM automatically displays repaired plan and recommends its immediate execution (FPM Mode – see below). If pilot complies, the PM executes the new plan and returns to *FPM Mode 2*.
5. Pilot selects one of the two remaining autonomy modes (see below): manual waypoint entry (Pilot Mode) or collaborative iteration (Hybrid Mode) to compute a mutually-optimal flight plan.
6. Pilot selects or alters the landing site, plan waypoints, and/or route segments. FPM validates pilot-altered segments against current performance and noise constraints, providing descriptive warnings if constraints are violated. Iteration continues until a plan is approved by the pilot.
7. FPM executes adapted flight plan and returns to *FPM Mode 2*.

Note that to maintain flexibility and pilot control authority, the FPM can be turned off at any time or can be engaged at any time to intercept the planned flight path at a nearby waypoint. Normally flight planning is performed prior to takeoff. However, full in-flight replanning is possible with the same algorithm by commanding the existing plan to execute in the background while replanning occurs, interrupting the plan repair process only to provide warning or critical status information. Significant interaction with the FPM is discouraged for single-pilot operations due to loss of current situational awareness. The FPM instead has a flight plan adaptation mode (autonomous FPM mode) that enables quick adjustments or provides procedures and safe alternative trajectories during high-workload emergency situations.

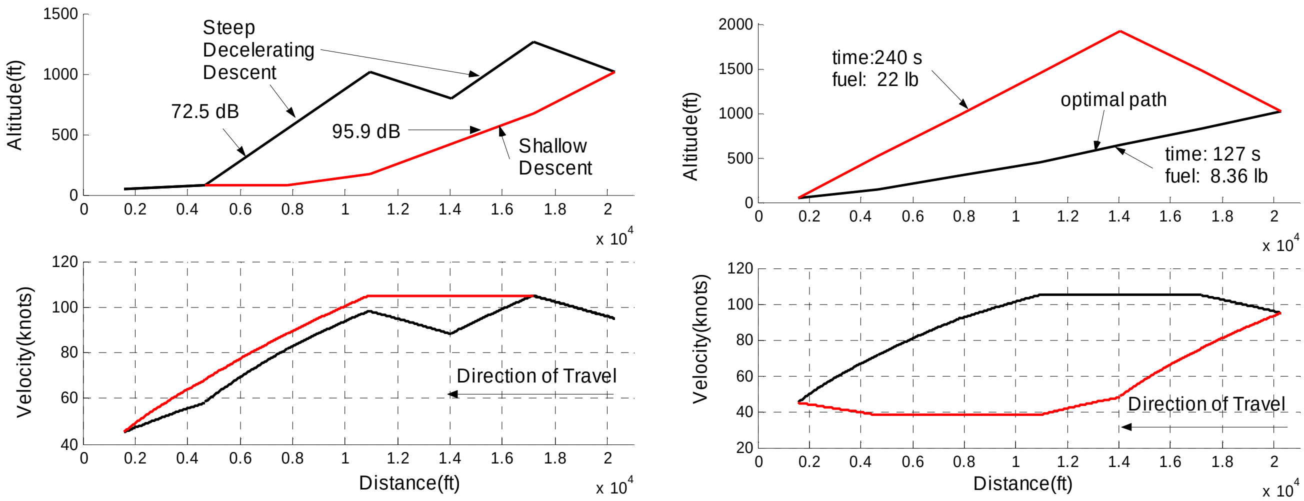
<u>Flight Trajectory Optimization</u>

The flight planner incorporates a multi-objective trajectory optimization capability to minimize radiated noise, flight time, and fuel expenditure. Approach and departure trajectory and PAV flight procedures are the foci of this work, utilizing the quasi-static performance and noise modeling approach [Gopalan et al 2000, Schmitz et al 2002] to compute and minimize noise-related annoyance in communities surrounding airports. Inclusion of acceleration/deceleration profiles enables a significant reduction in noise with minimal impact on time. Interactive map and noise profile displays enable the pilot to understand the effects of flight plan adjustments, creating a natural collaboration environment to facilitate the accommodation of FPM optimization processes alongside user-preferred routes. Gradient descent and A*-based route planning strategies [Gopalan et al, 2003; Xue and Atkins, 2003] have been developed for runway-independent aircraft simultaneous non-interfering approach procedure optimization, as illustrated for rotorcraft blade-vortex interaction (BVI) in Figure 5. These optimization techniques and cost functions are being integrated into the FPM and extended for fixed-wing engine and drag noise sources that complement the current rotorcraft BVI noise model.

<u>Real-time Flight Plan Adaptation</u>

Alterations to the flight plan can be required during flight due either to pilot-requested diversion or time-critical situations such as traffic conflicts or onboard systems failures. The preflight optimization tool will be re-used to accommodate non-critical diversions. A hard real-time plan repair strategy with variable autonomy levels based on previous work by the PI [Alonso-Portillo and Atkins, 2002] will be adapted for the FPM to promote safe operation by inexperienced pilots during unanticipated and potentially dangerous situations. This FPM mode will be activated by the flight plan monitor (mode 2), indicating that the existing flight plan requires repair. For most traffic and weather conflicts, flight path changes will strictly involve short-term deviations that intercept the original flight plan at a later point. System failure or severe weather that requires diversion to an alternate landing site will require a new set of waypoints that can be followed with a feasible trajectory. Feasible waypoint sequences must be constructed to connect current aircraft state with the new landing site, and real-time response is crucial for critical failures. Figure 6 shows the variable autonomy plan repair algorithm. For all autonomy levels, plan repair is a two stage process requiring identification of a feasible landing site and waypoint-based flight trajectory. In all modes, the *landing site search* module identifies and prioritizes a list of feasible landing sites based on aircraft footprint, reduced performance capabilities, and airspace/weather constraints. Once selected, a trajectory to that site is generated, approved by the pilot, and validated with the FPM [reduced] performance model.

FPM accommodates three levels of plan repair autonomy to enable collaborative, real-time plan development: (1) *Pilot Agent* in which the pilot selects the airport and waypoint trajectory using the prioritized landing site list as a guide, (2) *Hybrid Agent* in which the FPM suggests a feasible landing site and trajectory but allows the pilot to alter the landing site, waypoints, or trajectory details, and (3) *FPM agent* in which both landing site and detailed trajectory are autonomously selected by the FPM plan repair algorithms. The pilot agent represents the lowest autonomy setting. In this level, the pilot ultimately selects the landing site and plans the waypoint trajectory. The primary FPM challenge for safe flight is in conveying aircraft performance properties and the potential for conflicts such that the pilot makes a wise decision. *Hybrid agent*, an intermediate autonomy level, enables collaborative flight



a) Best and Worst-case BVI Noise Trajectories. b) Best and Worst-case Fuel Use Trajectories.

Figure 5: Effects of Flight Path and Acceleration on Rotorcraft BVI Noise versus Fuel.

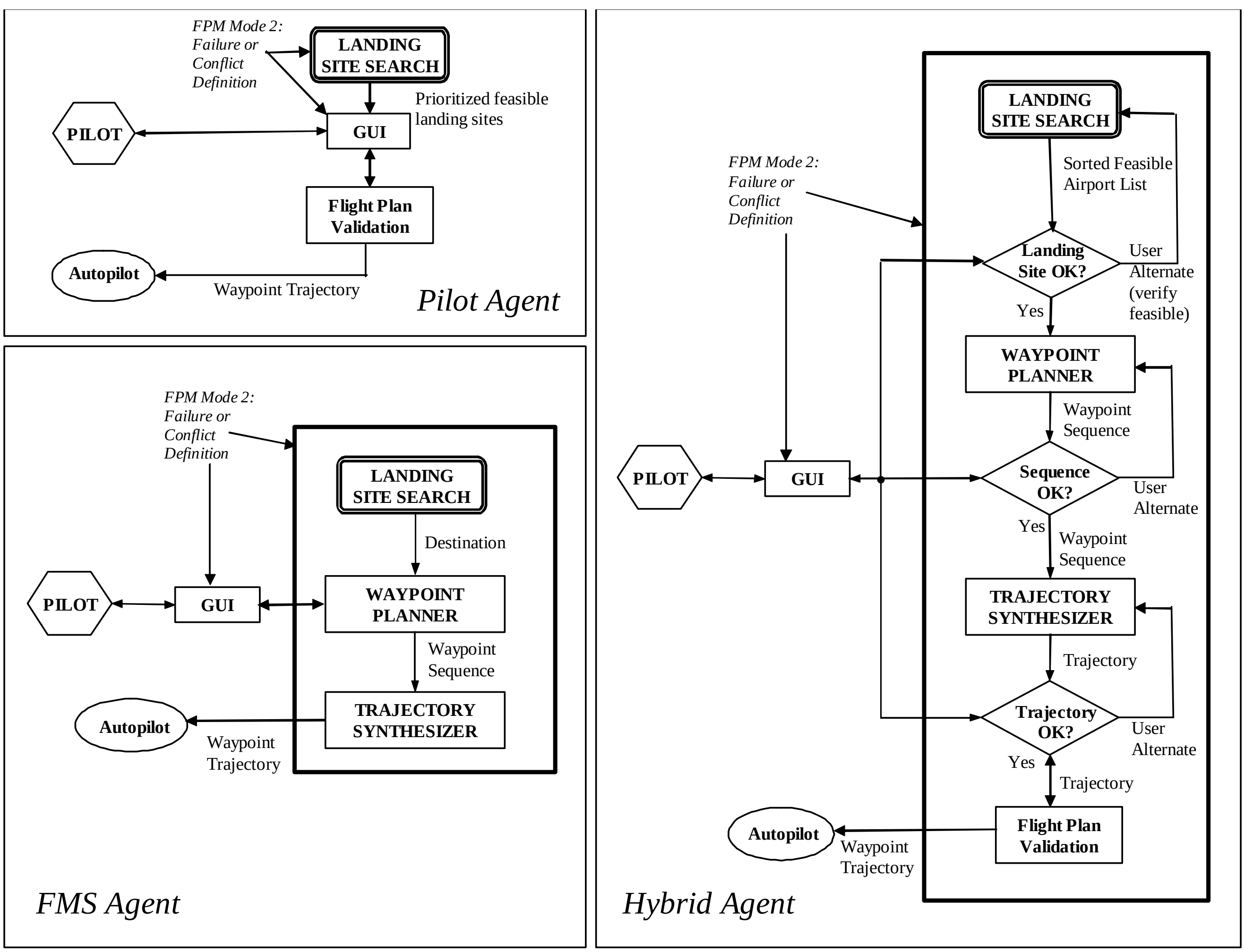


Figure 6: Variable Autonomy Plan Repair.

plan development. The FPM provides a prioritized landing site list. The pilot can select the top airport or a reachable alternate. The FPM Waypoint Planner builds/displays a sequence of route segments connecting current state and landing site, and the pilot can either execute or alter the waypoints and route properties until a mutually acceptable plan is identified. With the FPM agent, autonomous operation is achieved by selecting the highest-priority landing site and building a safe, feasible waypoint trajectory to this site. This mode will provide real-time response capability for time-critical situations, requiring the pilot only to accept the plan prior to execution.

Conclusion and Future Work

The flight plan management (FPM) software architecture presented in this paper integrates stand-alone noise prediction and safety-enhancing tools to enable the average person acting as PAV pilot to safely and efficiently manage flight operations. The trajectory optimization and noise modeling tools are also applicable to any PAV or general aviation (GA) system, augmenting existing technologies such as the affordable Garmin G-1000 glass cockpit system. The real-time flight plan validation and adaptation algorithms are essential enabling technologies before PAVs will be comparable in safety and ease of operation to an automobile, an ambitious goal of NASA's PAV program. A prototype system for a C-172 (under development) will enable detailed study of the algorithms and user interfaces, and will drive enhancement of all FPM technologies.

The proposed FPM architecture simplifies both offline and online flight planning processes. Flight safety, particularly for low-time pilots, will be improved in two ways. First, the FPM will validate flight plans against aircraft performance constraints. It also will improve safety, reducing pilot workload during in-flight emergencies by computing feasible trajectories and landing sites and by validating pilot-entered routes in the presence of traffic/weather conflicts and/or reduced performance capabilities. Advanced noise models (ANOPP from NASA) will be utilized and extended to fit within the FPM architecture, synergistically augmenting the FPM and ANOPP technologies as noise model refinements are developed.

The long-term goal of this project is to develop a low-cost commercial product for GA/PAV pilots. Safety, cost, and ease of operation are prerequisites to success. Low-noise approach and departures are required to enable the new vehicles to be "good neighbors" in residential environments. FPM is designed to address both fundamental operational and noise issues, and together with an autopilot will be integral to future PAV cockpits.

FPM provides a general-purpose variable autonomy advisory tool applicable to all pilot experience levels. It will be valuable both for low-cost GA/PAV and commercial operations with full flight management systems (FMS). Parallel research is in progress to develop a Pilot's Optimal Workload Reducer (POWR) for commercial and military FMS applications, concentrating on the development of pilot interfaces, trajectory generation tools, and control algorithms required to safely land an aircraft after a variety of severe emergencies caused by situations ranging from missile damage (e.g., loss of a wingtip) to failed control surfaces (e.g., a jammed aileron). Two specific noise abatement procedures have been hand-coded in today's flight management systems: throttle back after takeoff, and steepen glide path / throttle back on approach. Although these rules have provided significant noise reduction in sensitive areas surrounding major airports, the integration of more complete noise and population density models into the trajectory optimization (flight planning) algorithm will provide a more comprehensive and formal tool for building trajectories even for nominal situations (no emergency) that are safe and that further reduce the noise annoyance expected from frequent PAV/GA operations.

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