NASA/TM-2007-215090

The Naturalistic Flight Deck System: An Integrated System Concept for Improved Single-Pilot Operations

Paul C. Schutte, Kenneth H. Goodrich, David E. Cox, E. Bruce Jackson, Michael T. Palmer, Alan T. Pope, Robin W. Schlecht, Ken K. Tedjojuwono, and Anna C. Trujillo
Langley Research Center, Hampton, Virginia

Ralph A. Williams
Analytical Mechanics Associates, Inc., Hampton, Virginia

J. Bryan Kinney
Christopher Newport University, Newport News, Virginia

John S. Barry, Jr.
Lockheed Martin Engineering Services, Hampton, Virginia

December 2007

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers, but having less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results ... even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA STI Help Desk at (301) 621-0134

- Phone the NASA STI Help Desk at (301) 621-0390

- Write to:
  NASA STI Help Desk
  NASA Center for AeroSpace Information
  7115 Standard Drive
  Hanover, MD 21076-1320

NASA/TM-2007-215090

The Naturalistic Flight Deck System: An Integrated System Concept for Improved Single-Pilot Operations

Paul C. Schutte, Kenneth H. Goodrich, David E. Cox, E. Bruce Jackson, Michael T. Palmer, Alan T. Pope, Robin W. Schlecht, Ken K. Tedjojuwono, and Anna C. Trujillo
Langley Research Center, Hampton, Virginia

Ralph A. Williams
Analytical Mechanics Associates, Inc., Hampton, Virginia

J. Bryan Kinney
Christopher Newport University, Newport News, Virginia

John S. Barry, Jr.
Lockheed Martin Engineering Services, Hampton, Virginia

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

December 2007

Available from:

NASA Center for AeroSpace Information (CASI)
7115 Standard Drive
Hanover, MD 21076-1320
(301) 621-0390

National Technical Information Service (NTIS)
5285 Port Royal Road
Springfield, VA 22161-2171
(703) 605-6000

Table of Contents

Acknowledgements

The authors are indebted to Dr. Frank O. Flemisch, German Aerospace Center – IFS, who developed one of the cornerstones of the Naturalistic Flight Deck – the H-mode. In addition, Dr. Flemisch contributed greatly to the development of the concept of operations that is described in this paper. He also developed and co-implemented the prototyping facility in which many of these concepts were conceived and tested.

1. Executive Summary

Small aircraft are expected to play an increasingly important role in the nation's transportation system as very light jets (VLJ's) make air-taxi operations cost competitive with automobiles for regional travel. The crew-cost per seat-mile is higher on small aircraft than larger transport aircraft and while initially planning to operate with two-pilot crews, it is likely that increased use of single-pilot operations will be desired in the future if safety and airspace integration concerns can be addressed. At the same time, widespread air-taxi operations are likely to generate increased interest in self-flown operations as people experience the productivity of small aircraft and see self-operation as a means to lower costs and increase flexibility. Fractional ownership and rental businesses could make piston and turboprop aircraft financially practical for travelers of modest means and VLJ's retired from commercial, air-taxi operations are also likely to be financially attractive to private operators. Again, a significant concern is addressing safety and airspace integration issues stemming from increased, single-pilot operations, in this case for private pilots potentially having lower rates of exposure, a minimum of training and less formal oversight when compared to airline pilots.

In response to these pressures, this paper reviews current and emerging operational experiences, technologies, and human-machine interaction theories to develop an integrated flight system concept designed to increase the safety, reliability, and performance of single-pilot operations in an increasingly accommodating but stringent national airspace system. This concept, known as the Naturalistic Flight Deck (NFD), uses a form of human-centered automation known as "complemation" (i.e., complementary-automation) to structure the relationship between the human operator and the aircraft as independent, collaborative agents having complimentary capabilities. The human provides commonsense knowledge, general intelligence, and creative thinking, while the machine contributes specialized intelligence and control, extreme vigilance, resistance to fatigue, and encyclopedic memory. In general, tasks are structured so that the human is involved in actions and decisions having significant consequences on the overall mission and safety and less involved in actions and decisions that are relatively deterministic, time constrained, tedious, repetitious or require great precision.

To improve situation awareness and reduce the risk of mode confusion, tasks and their supporting interfaces are separated into two major partitions— the Actual and Notional systems. The pilot uses the Actual system to access information relevant to the immediate conduct and safety of flight (i.e., tactical information) and to control all functions that cause physical or external responses by the aircraft or its systems. The Notional System pertains to information and tasks used to support longer-range decision making (e.g., flight planning and in-flight strategic decision making) and development and maintenance of essential skills through review of previous flights and preview of planned or potential flights. The Notional system includes portable equipment facilitating use independent of a physical aircraft.

The Actual and Notional system behaviors and interfaces are shaped by design metaphors selected to simplify initial training, operational ease of use, and reinforce the desired pilot and automation relationships. The Actual system uses the metaphor of a well-trained horse to support and interact with the pilot. The horse metaphor has two important aspects. First, the vehicle has a "horse-like" degree of situation awareness, intelligence, transportation capability, and autonomy. Second, the horse and rider communicate with each other through coordinated multi-modal interactions that include a strong haptic (sense of touch and proprioception) coupling between their respective "wills" (which will nearly always converge rapidly on a shared, safe and appropriate action). As implemented in a vehicle, this "H-mode" interface provides a bi-directional connection that is more natural and efficient than traditional visual display/keypad interfaces for real-time, spatial maneuvering tasks. In the NFD, the haptic link will be implemented through an active (i.e., force-feedback) side-stick and speed command lever. Like a rider of a horse, the pilot can direct the vehicle through a combination of more automated, "loose rein", behaviors in which the vehicle has a relatively high degree of autonomy, and less automated, "tight rein", behaviors in which the pilot more directly controls the flight path of the vehicle. Also like a horse, the vehicle will autonomously react to pop-up hazards while continuing to support the pilot's near-term directives. The H-mode interface allows the pilot to "feel" the vehicle's intentions/preferences in such situations and intuitively redirect it if desired or necessary (e.g., shifting the vehicle's path around a conflict from a deviation to the left around to the right). Depending on the situation, the vehicle may readily adopt the pilot's redirection; or if perceived as inappropriate, will provide a measured degree of resistance to ensure that the pilot recognizes the system's reservations. Visual and auditory interface elements provide additional insight into the Actual systems status, perceptions, and future actions.

The Notional system is based on the metaphor of an electronic assistant such as a crewmember or flight dispatcher. The goals of the Notional system are to help ensure that the pilot is appropriately prepared before a flight (e.g., has the requisite certifications, currency, suitable equipment, performs expected pre-flight checks, etc.), understands the risks/issues involved in a potential or active plan, and is primed to recognize and respond to changes that may require an update to the current plan. During a flight, the Notional system is constantly assessing progress relative to expectations and monitoring current and forecast conditions along the route to help ensure that safety margins are maintained, regulatory requirements are satisfied, and pilot specified preferences or constraints are met. Integrated mission-status-graphics are proposed to provide the pilot with regular feedback from these assessments and provide convenient access to more detailed information as desired or needed.

To support the development of the NFD, an initial Concept of Operations (ConOps) has been created and selected normal and non-normal scenarios are presented in this document. These scenarios are used to illustrate key aspects of the human-machine interaction and the underlying roles and functional requirements of the human pilot and the airplane. The specific concepts outlined in these ConOps scenarios are initial baselines that will be refined or replaced as the overall system matures. A spiral development process using a range of realization fidelities including storyboards (e.g., ConOps scenarios), simulation prototyping, high-fidelity simulation, and flight development and evaluation will be required during this maturation process. During this process, it is vital to initiate and maintain a dialogue and partnership with potential pilots, commercializers (i.e., investors, manufacturers, marketers), and regulators to ensure that key opportunities, concerns, design guidelines and certification methods are addressed. This document is intended to be an initial element in this dialogue and feedback from the broader community is encouraged.

2. Nomenclature

ADS-B	Automatic Dependent Surveillance Broadcast
AOPA	Aircraft Owners and Pilots Association

ATC	Air Traffic Control
ATIS	Automatic Terminal Information Service
ATP	Airline Transport Pilot
CFIT	Controlled Flight Into Terrain
CFR	Code of Federal Regulations
CAMA	Crew Assistant for Military Aircraft
ConOps	Concept of Operations
DAG-TM	Distributed Air/Ground Traffic Management
DCL	Desired Configuration List
FAA	Federal Aviation Administration
FMS	Flight Management System
GA	General Aviation
GPS	Global Positioning System
GPWS	Ground Proximity Warning System
H-coa	H's center of attention
IAF	Initial Approach Fix
ITP	Interactive Trip Planner
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
MEL	Minimum Equipment List
MSL	Mean Sea Level
NAS	National Airspace System
NEXRAD	Next Generation Radar
NFD	Naturalistic Flight Deck
NextGen	Next Generation Air Traffic System
NOTAM	Notice To Airmen
NTSB	National Transportation Safety Board
PIREP	Pilot Report
RJ	Regional Jet
RNP	Required Navigation Performance
RVSM	Reduced Vertical Separation Minimums
SCAS	Stability and Control Augmentations System
SVS	Synthetic Vision System
TAA	Technically Advanced Aircraft

TCAS	Traffic Collision Avoidance System
VFR	Visual Flight Rules
VLJ	Very Light Jet
VMC	Visual Meteorological Conditions

3. Concept Goals and Objectives

3.1. Goals: Improving Aviation Safety, National Airspace Capacity, and Mobility

The trend over the past 10 years toward smaller passenger aircraft shown in figure 1 (Hansman, 2004) is likely to continue or accelerate in the coming decades. The use of smaller aircraft is likely to grow at a

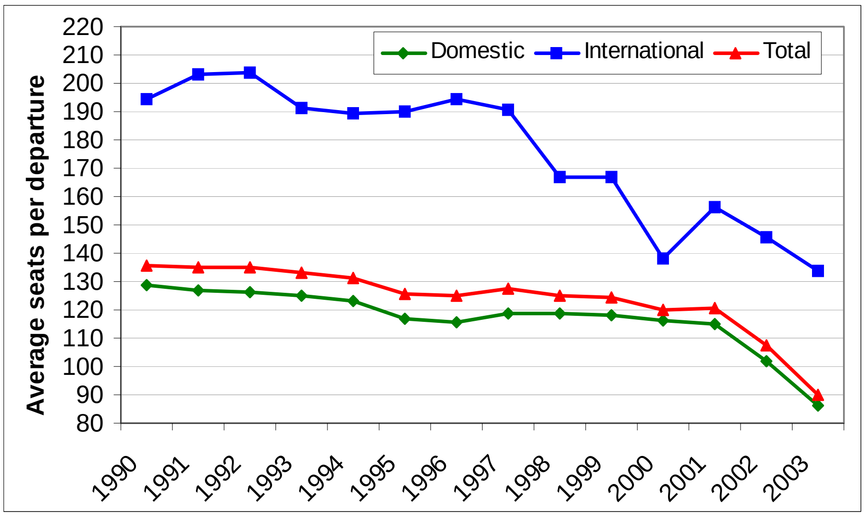

Figure 1: Trend to smaller aircraft

rapid pace as service providers strive to provide faster (e.g., direct flights) and more frequent service between a greater number of cities. Between 1998 and 2003, daily regional jet (RJ) operations increased by 356% (Mozdzanowska, 2004) and fractional ownership of business jets increased by 255%. As of January 2006 large scale, on-demand air taxi operations using very light jets (<6 passengers) are being planned by several companies such as POGO (www.flypogo.com) and Day Jet (www.dayjet.com).

As airplanes get smaller, the cost of the crew becomes a larger percentage of the cost of a flight and a dominant factor in the ability to provide competitive services. Considering the “Very Light Jet” (VLJ) class of aircraft such as the Adam A700, Eclipse 500, and Cessna Mustang, the demand analysis of Dollyhigh (2002) suggests significant demand sensitivity to price.

A key factor in growing beyond traditional markets for such aircraft is likely to be successfully operating with a minimal crew size. While present regulations (e.g., Part 91.1061 and Part 135.105) allow, with certain restrictions, carriage of passengers for compensation with only a single pilot, most of the current and planned services intend to use two pilots. This decision is probably influenced most significantly by customer acceptance and insurance costs. Customers for smaller airplanes may already be apprehensive about traveling in an aircraft significantly smaller than an RJ and the presence of a 2-pilot crew provides an observable representation of airline-like safety. In addition, without some sort of credible back-up, customers are likely to view a single-pilot as a potentially catastrophic, single point of failure. Another important factor favoring the use of 2 pilots is the cost of insurance. While direct comparisons between the safety of single and two-pilot operations are difficult to make due to differences in the types of operations typically conducted, current accident statistics suggest that even with comparable equipage and pilot experience, crewed operations are 4-5 times safer than single-pilot operations (Collins, 2003). As would be expected, insurance companies take this difference into consideration when setting rates and it is often less expensive to hire a second pilot than to pay the additional insurance premium for single-pilot operations (Benenson, 2003).

While the majority of early VLJ operations are likely to have 2-pilot crews for the above reasons, market forces are also likely to push to make single-pilot operations increasingly common if these disadvantages can be mitigated through other means such as improved technology. An opportunity exists to dramatically improve the safety and performance of single-pilot operations by considering the special needs of these operations and tailoring the design of the cockpit and supporting automation in light of available and emerging technologies and experience. Historically, there has been little difference between systems and automation designed for single-pilot and crewed aircraft, despite significant differences in the available human resources and ability of a crew to cross-check information, decisions, and actions. For example, there are no physical differences between the Cessna Citation I certified under Part 25 for crewed operations and the Citation I/SP certified under Part 23 for single-pilot operations. For single-pilot operations, the FAA requires an autopilot capable of flying coupled approaches, a squawk/ident switch on the yoke, and a boom microphone, items that were standard on both versions of the airplane. This lack of attention to the differing requirements and resources of single-pilot operations was perhaps the only practical approach prior to the advent of modern, digital systems. But, with the replacement of conventional, electromechanical systems with more capable digital systems, designing the cockpit and underlying automation specifically for such operations may dramatically improve the safety and performance of single-pilot operations. Furthermore, as the National Airspace System (NAS) continues to evolve, operations wanting to take advantage of the maximum efficiency and flexibility offered by the system will probably need to support reduced spacing initiatives (e.g., RVSM) and aircraft-based responsibility for traffic separation. These emerging requirements will further increase the challenges of safe and efficient single-pilot operations.

Recognizing this opportunity, this document outlines a concept for integrating current and emerging technologies into an integrated system specifically designed to support future single-pilot operations in small aircraft. The range of aircraft and operations considered in this document are aircraft certified under CFR 14 Part 23, classes I, II, and III (e.g., non-commuter category airplanes, < 12,500 lbs takeoff weight); having category A or B approach speeds (i.e., < 120 knots); and operated under Part 91 (private and fractional ownership programs) or on-demand operations under Part 135 with 9 or fewer passenger seats. While many of the concepts are applicable, in whole or part, to larger aircraft or two-pilot operations, the above vehicle classes and operations are considered the focus applications during discussion of the integrated design concept and applicable certification issues. Also, while the initial impetus and early adopters of the concepts discussed in this report are likely to be commercial operators that can gain economic benefits with minimal changes to existing regulatory statues and policies, it is desired that these same concepts can, with sufficient operational experience and maturation, form the basis for creating a new pilot rating (or alternatively a limited rating such as that issued for center-line thrust twins, for example) for pilots of appropriately equipped aircraft. Such a rating would consider the changed role and tasks of the pilot given the support of specified equipage and vehicle capabilities. The skill, knowledge, licensing, and currency requirements could thus be tailored for this new role with the goal of enabling safer, more capable pilots and operations with reduced formal instruction than nominally required for similar operations today. A long-term measure of success in this regard would be enabling persons of average ability and motivation and with a volume of training roughly equivalent to earning a private pilot certificate restricted to VFR operations today (~60 hours of flight training + ground school), to operate an appropriately equipped aircraft in IMC with a level of safety, mission reliability, and workload comparable to similar trips made by automobile.

3.2. System Objectives: Enable Single-Pilot Aircraft Operations

The overall system objectives are to enable single-pilot operations with safety and performance comparable to Part 121 operations. With this motivation in mind, the following high-level objectives must be supported by any viable system concept that seeks to address future single-pilot, small aircraft operations.

3.2.1. Safety consistent with broad public and institutional acceptance

- Objective: On a per trip basis, the risk of a serious or fatal injury should be less than comparable travel by automobile and ideally comparable to commercial air carrier.

- Rationale: Individuals and businesses often hesitate to utilize small aircraft due to both the perception of reduced safety and the reality that for many types of operations, the safety of small aircraft is less than that of other forms of transportation such as automobile or commercial airline (Guohua & Baker, 2007; Bureau of Transportation Statistics, 2007). A level of safety comparable to these other forms of transportation must be achieved and maintained if travel by small aircraft is to be a viable alternative for most people. Furthermore, this objective should be achieved for all classes of pilot certification and experience, not just highly experienced, commercial or ATP rated pilots. Achieving high levels of safety for all classes of pilot, including relatively inexperienced pilots in single pilot operations, is important to manage the public's overall perception of small aircraft safety and to ensure system robustness across a wide variety of pilots.

3.2.2. Compatible with Current and Likely Future Airspace Environments:

- Objective: The system concept must support single-pilot operations in current and likely future air space system concepts of operation including Required Navigation Performance (RNP) based navigation, forms of distributed air-ground traffic management with various levels of self-separation responsibilities, and emerging security considerations.

- Rationale: It is currently predicted that significant changes to the national airspace system are likely to occur over the next two decades. While these concepts are not yet firmly defined, general requirements on the vehicle segment of the NAS can be foreseen and incorporated into the system concept. Such requirements are likely to include reduced separation and self-separation during certain mission phases and procedures and operating in airspace in which 4-D RNP concepts are used to define navigation performance and containment. That said, the pace of evolution of the other portions of the NAS is unpredictable so it is important that the flight system concept not depend on the introduction of new technologies not already being implemented in other segments of the NAS.

3.2.3. Compatible with the Intent of Certification Regulations

- Objective: While not necessarily compliant with the letter of current regulations, the system concept must recognize the importance of certification and the need to design functions vital to safety and mission conduct such that credible methods exist or can be developed to verify the performance of these functions with the necessary degree of confidence.

- Rationale: To be relevant, concepts must be certifiable. However, this requirement should not be in the sense of strict compliance with current regulations. Rather it should be done through application of a comprehensive system-safety analysis that considers the faults of both technology and human elements and achieves an equivalent or better level of safety than achieved with present practices. A key issue will be the appropriate integrity of aircraft systems that augment or perform tasks currently performed by the pilot and are critical to continued safe flight and landing. Traditionally, the pilot is relied upon to perform the vast majority of tasks critical to safety of flight as this avoids the burden of certifying such systems and the liability if there is a suspected failure. For example, in most small airplanes today, the pilot is relied upon to cross-check the basic flight instruments to detect and isolate failures of the pitot-static and gyroscopic instruments. Multiple accidents a year are typically attributed to failures to adequately perform this task. An automated system could perform this task in place of the pilot with much higher reliability, but such a system currently has to satisfy the flight-critical certification requirements of 23.1309 as a system failure could be catastrophic. Meeting these requirements could be extremely costly. From a system-safety perspective, having automation reliability one or two orders of magnitude greater than human performance for the same task would provide an overall safety benefit, despite not meeting the current requirement. In addition, having automation perform this constant, visually intensive monitoring task would allow the pilot to allocate their limited sensory and cognitive resources to other tasks for which they are better suited, further improving safety beyond the direct comparison of performance on this isolated monitoring task.

3.2.4. Trip reliability comparable to commercial airlines

- Objective: In addition to providing a high level of safety, the system concept must be consistent with providing trip reliability comparable to commercial air travel.

- Rationale: Travelers need to be able to rely on completing flights such that the underling purposes of the trips are not significantly impacted. Table 1 indicates that commercial flights are delayed more than 15 minutes approximately 22% percent of the time and cancelled 2.4% of the time. Given that the hub and spoke system requires the typical traveler to make two flights between that true origin and destination suggests that the probability of having one of the legs delayed is 39% while the risk of at least one leg being cancelled is 4.7%. While cancellation of a leg is likely to impact the trip significantly (e.g., causing an unplanned overnight stay or inability to make a mid-day meeting), the impact of a delay is less certain depending on whether it results in a missed connecting flight. In the absence of objective data on this subject, it is estimated based on anecdotal experience that 20% percent of these delays cause a significant impact on the trip, defined as arriving at the final destination later than 2 hours after the planned arrival. Together, these significant delays and outright cancellations result in less than 90% probability of completing a trip as planned using commercial air transportation.

Year	On time Arrivals	On time (%)	Arrival Delays	Delayed (%)	Flights Cancelled	Cancelled (%)	Diverted	Flight Operations
1997	4,218,165	77.94%	1,083,834	20.03%	97,763	1.81%	12,081	5,411,843
1998	4,156,980	77.20%	1,070,071	19.87%	144,509	2.68%	13,161	5,384,721
1999	4,207,293	76.11%	1,152,725	20.85%	154,311	2.79%	13,555	5,527,884
2000	4,125,263	72.59%	1,356,040	23.86%	187,490	3.30%	14,254	5,683,047
2001	4,619,234	77.40%	1,104,439	18.51%	231,198	3.87%	12,909	5,967,780
2002	4,329,635	82.14%	868,225	16.47%	65,143	1.24%	8,356	5,271,359
2003	5,317,886	81.96%	1,057,804	16.30%	101,469	1.56%	11,381	6,488,540
2004	5,566,323	78.08%	1,421,406	19.94%	127,757	1.79%	13,784	7,129,270

Note: For purposes of this report, a flight is considered delayed if it arrived at (or departed) the gate 15 minutes or more after the scheduled arrival (departure) time as reflected in the Computerized Reservation System.

Table 1: Schedule Performance for Commercial Airlines

3.2.5. Effective use of Technology

- Objective: The technology employed in the system concept cannot be less cost-effective than operating with a second pilot.

- Rationale: The goal of the overall activity is to achieve the benefits of single-pilot operations while improving the safety and performance of such operations in an increasingly demanding airspace environment. As such, if a proposed system concept were less cost effective than simply operating with 2 pilots, this concept would not be viable. For comparison purposes, from secure.salary.com, the co-pilot of a small (<12,500lbs), non-jet airplane earns a median salary of $52,000 per year. Assuming benefits and payroll taxes are 30% of direct salary expenses, and $10,000 annually for recurrent training, the annual cost of a co-pilot is $78,000 per year, or assuming 1000 flying hours per year, $78 per hour. Components of life-cycle, system cost include initial development, certification, component costs, maintenance, initial and recurrent pilot training, crew cost, passenger/cargo capacity, and operational impacts of missions not completed due to lack of capability or system failures. Since performing a rigorous analysis of life-cycle cost of as yet developed technology is not possible, this objective will be applied in a more qualitative sense. Also, greater emphasis will be placed on recurring costs than nonrecurring development costs since much of the development costs will be covered under this program.

4. Overview of Current System Performance

For complex, safety-critical systems such as the civil air transportation system, current system operations and performance should be used as a benchmark for proposed improvements. This section provides a brief overview of current and emerging small aircraft operations and technologies, highlighting areas of particular relevance to the objectives described earlier. Small aircraft are currently benefiting from an influx of new technologies similar to those introduced in the "glass flight deck" in commercial aircraft in the mid 1980's. Because of the significant technological differences between airplanes that make up the majority of GA aircraft and the minority of GA aircraft that have state of the art avionics, this section is divided into two subsections. Section 4.1 deals primarily with experiences of the more common GA aircraft while section 4.2 deals with the current and emerging state of the art.

4.1. State of the Practice

The operational safety record of small aircraft is regularly summarized and analyzed by the National Transportation Safety Board (NTSB) and, for general aviation operations, the Aircraft Owners and Pilots Association (AOPA). Interested readers can download annual reports from these organization's websites. While accident rates have trended downward over the past several decades, their primary and contributing causes have tended to remain the same and are very similar to commercial Part 121 operations, suggesting that strong, underlying factors are present. Table 2 (NTSB, 2004) indicates the ten most common occurrence chains for fatal GA accidents in the year 2000 while figure 2 (Boeing, 2004) indicates the primary types of fatal accidents for worldwide operation of commercial transports between 1994 and 2003. Loss of control and CFIT are by far the primary causes of fatalities in both domains. Figures 3a and b (AOPA 2003; Boeing, 2004) show accident and fatality occurrences as a function of phase of flight, again showing similarities between GA and commercial operations. "Maneuvering flight" is largely unique to GA operations and includes activities such as practicing emergency procedures at low altitudes. Flight crew actions are identified as the top causal element in both large and small aircraft as shown in figures 4a and b (NTSB, 2004; Boeing, 2004). Taking a more detailed look at accidents attributed to human error, Weigmann and Shappell performed an analysis of commercial (Parts 121 and 135) (2001) and GA (2005) operations using a "human factors analysis and classification system" found that skill-based errors are the most common type of human error in both domains as shown in figure 5, with other error types such as decision errors and violations (e.g., going below minimums) playing important but lesser roles. Skill-based actions are actions performed without significant conscious thought such as stick and rudder manipulation or visual scanning. They often rely on practiced behaviors and are susceptible to attention or memory failures.

Rank	Chain Of Occurrences - Fatal GA Accidents, 2000	Number of Accidents
1	Loss of Control In-flight → In-flight Collision with Terrain/Water	95
2	In-flight Collision with Terrain/Water	47
3	In-flight Collision with Object	25
4	In-flight Collision with Object → In-flight Collision with Terrain/Water	17
5	In-flight Encounter with Weather → In-flight Collision with Terrain/Water	15
6	Airframe/Component/System Failure/Malfunction → In-flight Collision with Terrain/Water	9
7	In-flight Encounter with Weather → Loss of Control In-flight → In-flight Collision with Terrain/Water	8
8	In-flight Encounter with Weather → In-flight Collision with Object	7
9	Loss of Control In-flight → In-flight Collision with Object	7
10	Airframe/Component/System Failure/Malfunction → Loss of Control In-flight → In-flight Collision with Terrain/Water	6

Table 2: Ten most common occurrence chains fatal GA accidents

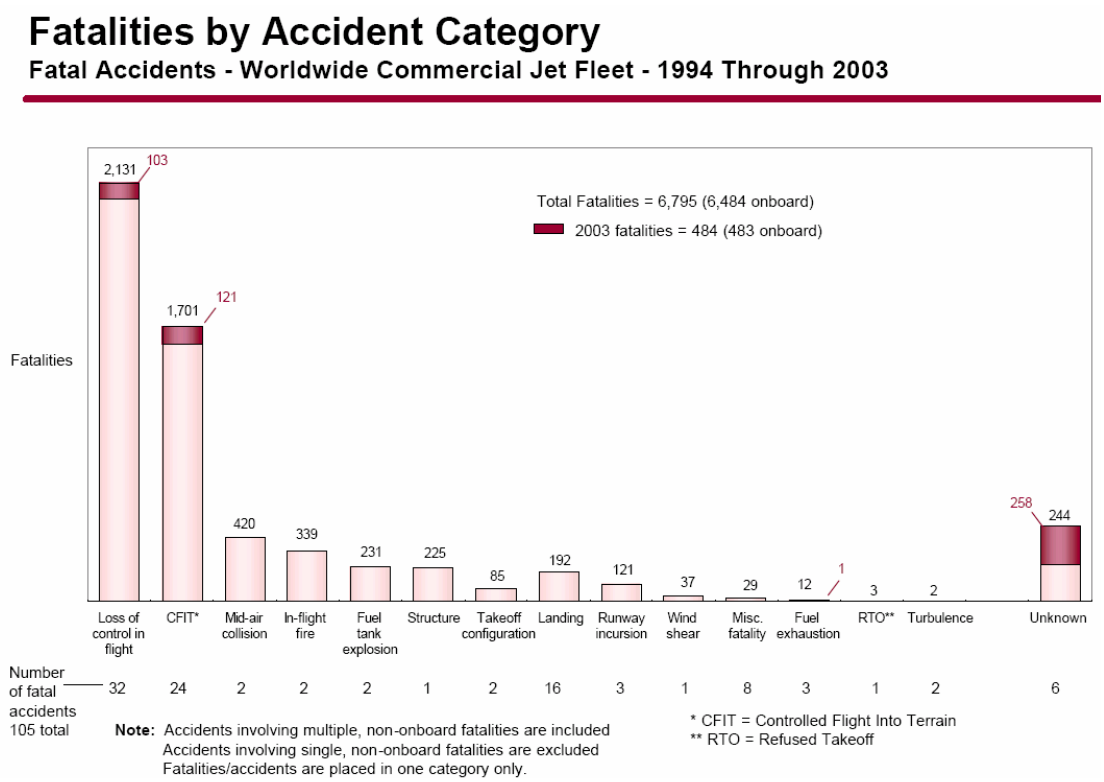

Figure 2: Primary types of fatal accidents for worldwide operation of commercial transports

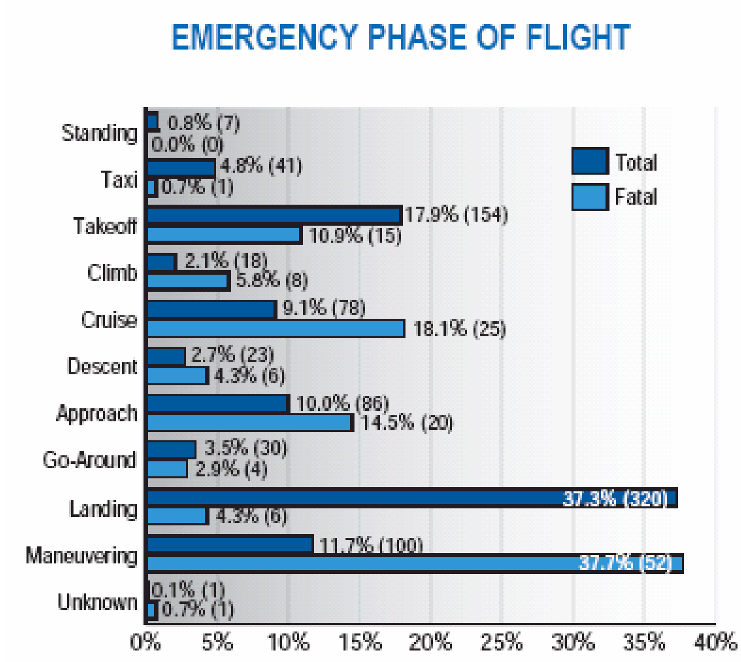

Figure 3a: Accident and fatality occurrences as a function of phase of flight

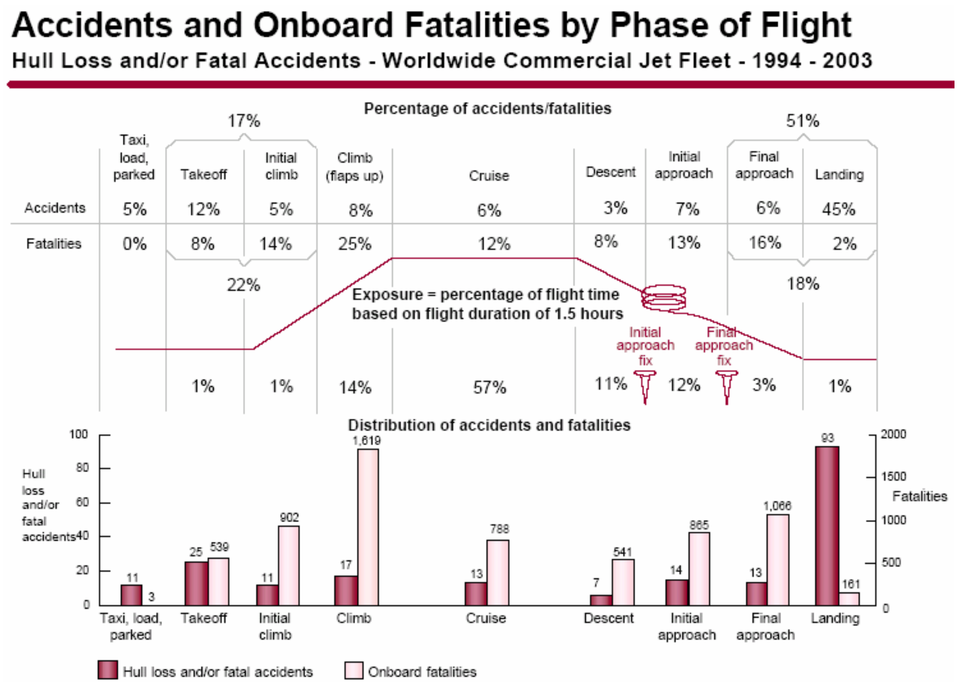

Figure 3b: Accident and fatality occurrences as a function of phase of flight

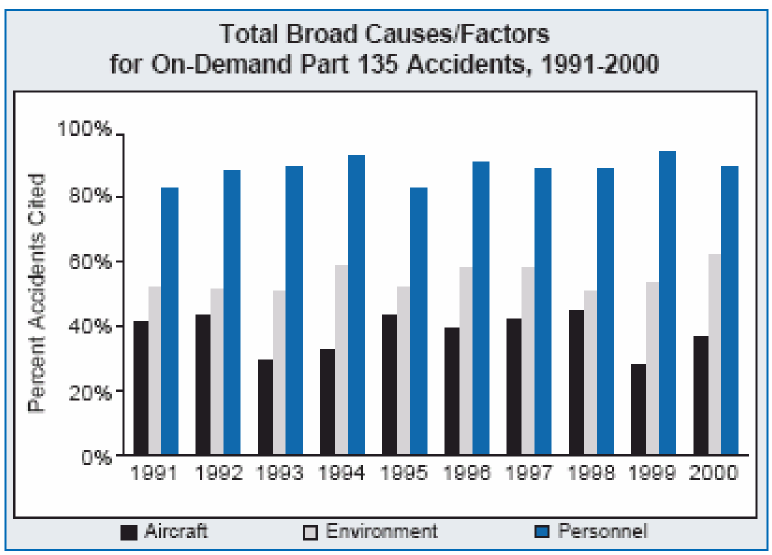

Figure 4a: Causal factors in aviation accidents

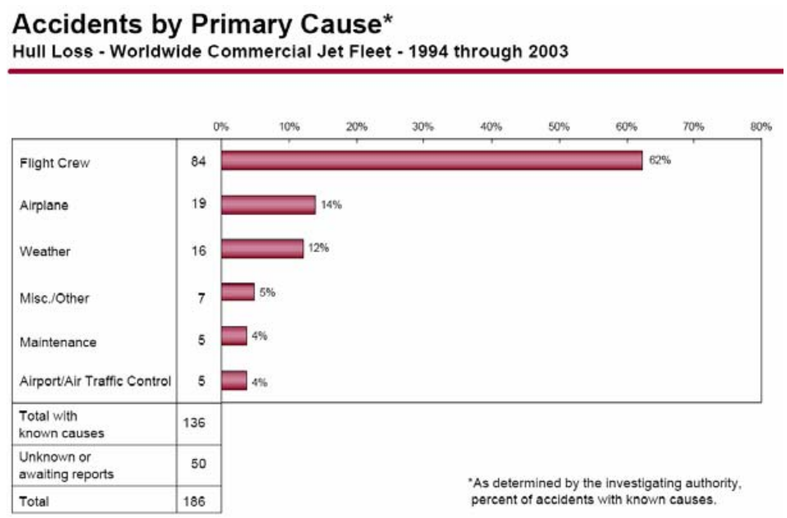

Figure 4b: Causal factors in aviation accidents

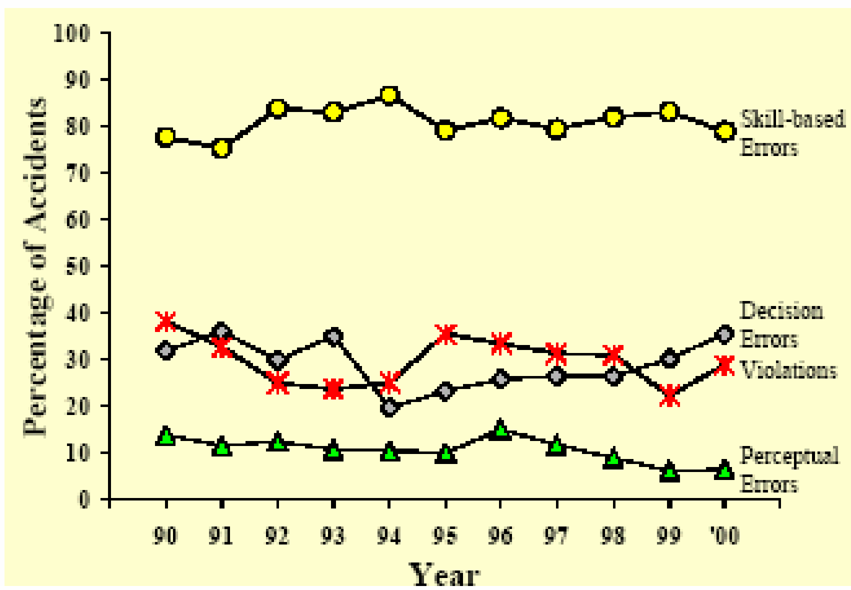

Figure 5: Contribution of human error types to accidents

Some general observations that can be drawn from these studies are that accidents tend to occur during phases of flight involving a high number of critical and/or complex tasks. Task criticality is usually increased with proximity to terrain and obstacles in that the time available to detect and recover from an error is reduced. Critical tasks are not necessarily difficult to perform but are often unforgiving and a momentary lapse in a task such as poor speed control resulting in a low altitude stall/spin may be disastrous. Other types of errors such as decision errors are important, but can often be corrected before an accident occurs. Since the flight crew currently has responsibility for performing the vast majority of critical tasks, it is not surprising that human error is found to be the top causal factor of accidents. A more constructive observation would be that critical tasks, whether performed by humans or the machine, need to be designed for fault tolerance. This is already a requirement for the vehicle's systems; per Advisory Circular, 23.1309-1c, at the vehicle level, no single failure can result in a catastrophic failure condition. This same philosophy must be extended to include the pilot as part of the pilot-vehicle system if significantly higher levels of safety are to be achieved.

The studies/reports referenced thus far are not specific to single-pilot operations and represent a mix of single-pilot and crewed operations. Studies of single-pilot incidents and accidents (e.g., Bergeron, 1980 and Forsyth, 1978) have found generally similar types of accidents and relative importance of causal factors. As would be expected, the generally higher workload and vulnerability to human blunders are identified as sources of increased risk for single-pilot operations.

In addition to strategies for improving safety, current operations provide insight into necessary capabilities for achieving or exceeding airline like mission reliability. In a survey of current general aviation pilots by Downen and Hansman (2002), weather and its impact on trip reliability was the number one factor cited in choosing other modes of transportation over small aircraft. The primary concerns reported by these pilots were thunderstorms and icing conditions. At the same time, very experienced pilots such as Collins (1993) report relatively high trip reliability (e.g., 94% of trips completed essentially as planned), even while scheduling these trips in advance before reliable weather forecasts are available; operating from the Northeast US with its difficult winter time conditions; and with a basic airplane (e.g., Cessna 182 without weather avoidance or icing protection equipment). Given weather avoidance equipment (e.g., radar, storm scope) and ice protection systems, experienced pilots report trip reliability in small aircraft that exceeds scheduled airline performance for practical purposes. Thus, airline-like reliability is achievable with current technologies for most classes of aircraft. That said, most pilots do not feel comfortable operating in hard IMC in small aircraft with minimal IFR equipage. They desire a greater degree of weather awareness and equipage including the ability to tactically avoid thunderstorms and manage icing encounters. These capabilities should be part of the basic, integrated system needed for robust, near-all weather transportation.

4.2. Current and Emerging State of the Art

Avionic systems on state-of-the-art small aircraft are rapidly becoming as, or in some regard more, sophisticated than the most sophisticated transport category aircraft. One reason for this trend is that certification requirements for small aircraft certified under CFR 14 Part 23 are less demanding than for transport aircraft certified under CFR 14 Part 25, thus accommodating greater innovation. Another reason is that the decentralized operations typical of small aircraft favor increased reliance on aircraft-based capabilities versus the ground equipage that is often favored by commercial operators. Examples where small aircraft are leading commercial aviation in the adoption of new technologies are use of Automatic Dependent Surveillance Broadcast (ADS-B) and synthetic vision systems (SVS) (e.g., http://www.alaska.faa.gov/capstone/)

The impact of these innovations on the overall safety and utilization of small aircraft is not yet known, but some early observations are possible. First, certain types of accidents such as controlled flight into terrain (CFIT) can be largely eliminated. Figure 6 shows the number of CFIT accidents before and after mandatory ground proximity warning system (GPWS) equipage of turbine aircraft with 10-30 passengers. Given that CFIT is historically one of the top two most common fatal accident types, this trend suggests the overall safety rate should be significantly improved.

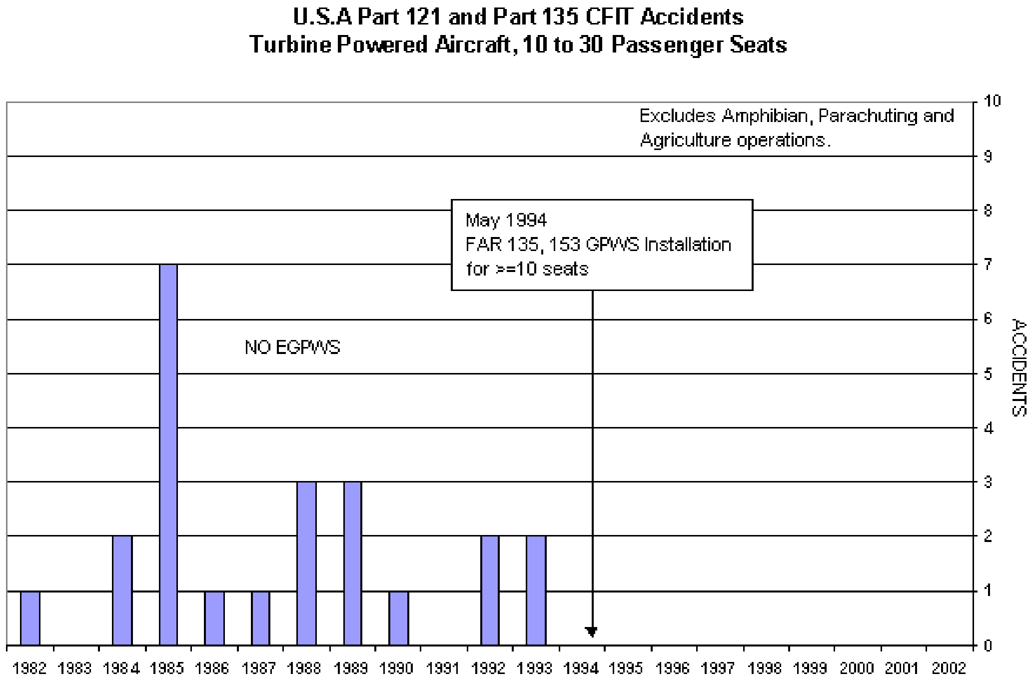

Figure 6: Effect of GPWS on CFIT accidents
(http://www.egpws.com/general_information/description/effective.htm)

That said, these improvements do not come without some concerns. Early accident rates for certain technically advanced single-engine, GA aircraft have been comparable to existing aircraft, prompting the FAA and industry to investigate the phenomena and publish a report on “Technically Advanced Aircraft” or TAA’s (TAA Safety Study Team, 2003). Key findings are that technology can increase the “available” safety, but contemporary installations require additional aircraft/system specific training to take advantage of the equipment and that technology has the potential to increase workload and may distract the pilot from other important responsibilities. As noted in the TAA report, these issues are consistent with previous introductions of new technologies in aircraft and should not overshadow the overall benefits new technologies may offer. Of course, designers must also strive to learn from these historical examples in order to anticipate and minimize any adverse aspects of future designs.

With technology currently available on certified small aircraft, the vehicle’s systems have access to much of the functionality and information critical to the successful conduct of a flight. Integrated navigation systems maintain continuous position awareness and combined with terrain, weather, traffic, and airspace data, represent a high degree of information about the external situation. Solid-state attitude, heading and air data sensors combined with full-authority digital engine control systems, digital autopilots, and highly automated secondary systems have a significant amount of information regarding the vehicle’s situation and actions. At present, much of this information simply passes through the vehicle on its way to be displayed to the pilot. The pilot is relied on to perceive the information’s significance, form an integrated understanding of the situation, develop potential actions, select a preferred course of action, and configure the systems to execute or assist the performance of these actions. This situation is the result of piecemeal technology evolution as individual systems were replaced by digital counterparts or augmented by new stand-alone systems (e.g., Traffic Collision Avoidance System, TCAS) without revisiting the basic role of the pilot or ability of the vehicle assist the pilot more effectively. Many vehicles appear autonomous because they can operate for long periods of time without any direct human involvement (essentially takeoff to touchdown), but are in fact only executing actions pre-sequenced by a human. Such a vehicle has no understanding of the context or advisability of its actions, let alone how to modify them should an unanticipated situation arise. At the same time, the pilot is left with a passive monitoring task, which often has no negative consequences if not performed. As described by many authors on automation design issues (Billings, 1997 Bainbridge, 1983, Norman, 1990), this situation is prone to a variety of failures and breakdowns.

As Norman (1990) remarks,

> "*Automation is at an intermediate level of intelligence, powerful enough to take over control that used to be done by people, but not powerful enough to handle all abnormalities. Moreover, its level of intelligence is insufficient to provide the continual, appropriate feedback that occurs naturally among human operations. This is the source of the current difficulties. To solve this problem, the automation should either be made less intelligent or more so, but the current level is quite inappropriate."*

Significantly improving the safety and capabilities of single-pilot operations in an increasingly demanding NAS environment is probably not achievable without reliance on sophisticated automation and thus requires following the path of more intelligent automation. In the remainder of this paper, a flight system concept for improved single-pilot operations is developed. This concept known as the Naturalistic Flight Deck (NFD) consists of largely existing, and often certified technologies, but strives to dramatically improve performance by developing a higher level of machine awareness and intelligence through information fusion and using this awareness and intelligence to create a new, more effective, partnership between the pilot and the aircraft. The NFD is described in the following sections by reviewing key concepts of human-machine interaction, describing the major system components, and then illustrating the operation and interaction these components through a selection of concept of operations scenarios.

5. Theoretical Concepts

Before describing the concept of operations, it is important to provide some theoretical perspective regarding the underlying assumptions in the design. Many of the concepts described later reflect a departure from the traditional way of thinking with respect to flight deck design. It is important for the reader to understand the mindset and framework of the designers in order to better appreciate the design. There are four primary theoretical concepts that will be discussed. The first is complementary automation or Complemation. This involves taking a very hard look at what the role of the human in the system should be and then designing the automation to support that role and overcome the human's deficiencies. The second concept is Engagement. Providing effective and acceptable ways of keeping the pilot in the loop while not creating intolerable levels of mental and/or physical workload. The third concept is the use of metaphorical design as a method to reduce training time and increase pilot situation awareness with regard to the responses of the system. Different pilot roles and automation capabilities will require different metaphors. Finally, a distinction is made between actually doing something and thinking or planning about doing something so as to avoid confusion regarding what the automation is going to do and who/what is in control (human or automation). All of these concepts fit together in the holistic design of the flight deck.

5.1. Complemation

We live in a world where errors are made by humans and errors are corrected by humans. Humans make errors in design, manufacture, direction, operation, and maintenance. At every stage of implementation and execution, humans can introduce errors and mitigate them. Conventional thinking claims that removing the human interaction and replacing it with machines will remove human error. However, this thinking overlooks two important considerations. The first is that humans are involved at some point in virtually every human endeavor, so it is nearly impossible to completely remove the human (e.g., removal of the human from operations via automation will simply move human errors to the design phase). The second consideration is perhaps more meaningful—the human's ability to prevent and mitigate unforeseen contingencies or situations.

Recent history is replete with examples of design, manufacturing, and maintenance errors causing severe failures (e.g., electrical power grids, airline and airport dispatch operations, and autonomous vehicles) that could have been prevented had there been the opportunity for some form of human intervention. In most of these cases the designers, manufacturers and maintenance personnel "failed to anticipate…" or "did not consider…" some combination of factors or occurrences. This situation is not surprising given that in complex systems there are essentially an infinite number of potentially significant factors and interactions. If a human had had some level of access to the system during operation, he might have performed a simple action, such as isolating a section of the power grid or correcting for an erroneous piece of data, that could have prevented or mitigated the failure. While supporting such access is often rejected based on statistics implicating the pilot as the top causal factor in current accidents (e.g., Figure 4), it is extremely important to recognize that no comparable data is recorded on successful human interventions (indeed, we are not sure how such data could be collected), that is, the number of failures, errors, and ultimately accidents that are avoided or remedied by human actions. Without data on beneficial interventions, using accident statistics to advance the case that human pilots "usually" make things worse and thus their system access should be minimized or eliminated is misleading and would be like saying that because engine failures lead to crashes, engines cause aircraft to crash and should be eliminated. Based on such flawed logic, traditional automation philosophy tends to throw the baby (human prevention and mitigation abilities) out with the bath water (human error).

Complemation (Schutte, 1999) or complementary automation offers a better alternative. Complemation does not remove the human from the operational aspects of the mission; rather it takes advantage of the human's unique abilities. Complemation deals with errors that the human pilot could potentially introduce into the system by reducing the proneness of the system to human error, identifying human errors and making them apparent to the pilot, and providing prophylactic measures to insure that human errors do not propagate throughout the system causing a failure. Thus, the machine and the human work together in symbiosis. The human pilot provides common sense knowledge, general intelligence, and creative thinking while the machine provides swift and precise control, extreme vigilance, resistance to fatigue, and encyclopedic memory. The human pilot has many tasks but perhaps the most important one is to compensate for limitations of other parts of the system or put more simply, to handle the unexpected.

5.1.1. Role Allocation and Support vs. Function Allocation

Unlike machines, humans cannot be built-to-order by designers to perform specific tasks; at best they are trained to perform tasks but there are limits to training. Humans have a limited operational envelope and require specific information in order to do their job. They are limited in memory (Baddeley, 1998), endurance, and other abilities such as computation. If the human is required to perform outside of this envelope or without sufficient information, they will fail. For example, a human who is asleep and is abruptly awoken to perform an assessment and decision making task quickly will more than likely perform it poorly. One reason is that human mental processes are usually sluggish on awakening from sleep. They require time to warm up. Another reason is that the human has been blissfully unaware of what has been going on in the surrounding world while asleep. Making assessments requires data and the human has not been acquiring data. In addition, humans respond very differently under stresses such as time pressure and in some individuals, reasoning under stress is extremely difficult.

In the past, allocating tasks to the human or the automation has usually followed a Fitt's List approach where a task decomposition was performed on the mission and tasks were assigned to whomever could perform them best. There are several flaws in this process. The first assumes that humans can perform the task well in isolation – that is, without any context or involvement in other tasks. For example, humans are better at performing qualitative value judgments and pattern recognitions. However, if the automation has been assigned tasks that remove the human from the information used to make these assessments, then the human will be hampered in performing them. Humans like to perform continuous, logical, and meaningful tasks in context, while the automation can easily perform every other step with the same accuracy as if it performed every step. The point here is not that humans have to be involved in every task but that the tasks must be grouped or chunked into meaningful and logical sets and assigned based on those sets. The second flaw in this argument is the premise that the tasks that humans do better than machines are tasks that humans do well. This is often not the case. Often the tasks that humans do better than machines are difficult even for humans. Thus the human is assigned the most difficult leftovers resulting in a high probability of an eventual human error. Yet another problem with traditional function allocation is that machines do routine things very well and therefore are usually assigned these tasks. This would be fine except it leaves the human with little to do most of the time and the human may become bored or complacent, ultimately loosing the necessary level of awareness needed to effectively understand the status of the mission and automation and leaving them vulnerable to potentially life-threatening surprises. As a result, pilots often refer to flying modern, highly automated aircraft as hours of boredom punctuated by moments of terror.

For these reasons, a new allocation strategy is required. The one that is proposed for this project is based on the general role that the human is going to play in the mission (including the roles the human may be called on to play in non-normal situations). The knowledge, skill, information, and control requirements are determined for performing these roles. The next step is to determine where the human may be weak and can use some help. The machine is then designed around those needs. The reason for this approach is that humans are less 'designable' than machines. We can design a machine around a human but we cannot design a human around a machine. At best, we can train the human but that has its limits, is costly and ultimately results in an increased probability of serious errors.

We propose that the human has the following roles in the NFD. First, the human is a mission director – choosing where to go, when to go, approving how to go, and when to make major changes in the plan. The next role is a consequent of the role of director and that is the role of mission troubleshooter. In this role, the human must monitor the status of the mission, environment, and airplane relative to expectations to identify and resolve issues that will or may impact the success and safety of the mission. Resolutions in this role would tend to be discrete decisions and actions such as modifying the flight plan to divert around an area of thunderstorm activity in response to loss of tactical weather information. The final role for the human is as a back-up for selected automation functions. This differs from the role of troubleshooter in that not only must the human decide on a remedial action, he or she must take an active role in replacing some functionality of the automation. For example, if the automation normally negotiates with ATC over data link, the pilot may have to step in and use voice communication if the data link system onboard the aircraft fails.

Each of these roles has certain fundamental information and control requirements. However there are additional requirements that must be met because the agent performing these roles is a human rather than a machine. For example, suppose that a requirement for performing a role is positional awareness. A machine can instantly read positional information and process it – even if it has not been monitoring that information. Humans, however require more time if they have not been monitoring this information than if they had been monitoring it. If they already have this information in their heads, humans often perform as swiftly as machines in making their assessments. But, if they have to ‘fill up their heads’ with the information, there can be a significant delay and processing deficit. In summary, there are requirements for performing in the role in general, and there are additional requirements for humans performing in the role.

5.2. Engagement

As hinted at above, getting information into the head or working memory of the human is one of the more difficult tasks. There is limited input bandwidth, the human can only focus on a limited area of that bandwidth at a time (e.g., auditory inputs are often ignored in the presence of strong visual or tactile inputs (Best, 1999)), and the human may forget previously received information. Humans are quite adept when it comes to prioritizing mental tasks and if there has been no reason for attending to a channel of information over a period of time, the human will stop attending to it. If we are watching a machine or another person perform the same task flawlessly over and over again we will find it hard to attend to it – even if we are expected to monitor that task. Our minds are naturally wired to attend to more dynamic things and tune out monotonous things regardless of importance. These states of tuning out could lead to what Pope (Pope & Bogart, 1993) refers to as a hazardous state of awareness. Hazardous states of awareness include high workload times where the human is stressed but also extremely low workload times where the human can become complacent or bored. While humans can be trained to counter this tendency, training only goes so far and is often time consuming and costly and many individuals will never achieve sufficient ability (e.g., individuals with attention deficient disorder provide an extreme example).

The challenge for the designer is to have the pilot update his mental model at an appropriate frequency without becoming annoyed. A classic example of this in aviation is the use of position reports. For oceanic flights, which are particularly monotonous, pilots are required to report their position at regular intervals.

The primary purpose of this task is to keep air traffic control aware of the aircraft’s location since it is out of radar coverage, however it also serves to update the pilot’s mental model. This procedure is effective because the primary purpose of the position report is not to update the pilot’s mental model – if that were the case the pilot might consider it busy work. Humans like to have meaning in their lives and they like to do things for a purpose. The NFD concept seeks to keep the human’s mental model up-to-date by providing active involvement in flight activities – specifically the human will initiate significant speed and trajectory changes at the time of execution. This is a radical departure from current automation trends toward preprogrammed flight. It appears to be underutilizing technology. However, this is only true from the traditional function allocation approach. That is, traditional functional allocation would state that because machines are more vigilant and have better memory than humans, they should be responsible for making speed and trajectory changes based on a preprogrammed route. However, from the role support perspective, this severely handicaps the human as mission director because now the human must remember what was programmed far into the future. In addition, the human must remember how the machine will execute the programmed commands. And since the machine will perform the task very reliably 99.9% of the time, the human will probably not be vigilant and paying attention during that 0.1% of the time where he or she is required to become involved. This loss of awareness and resulting confusion frequently manifests itself in modern commercial flight decks where the pilots misidentify what mode the aircraft is in, what automation system is currently controlling, or what the next automated action will be.

So the reasoning behind the design of the NFD goes as follows: What is the role of the pilot on the flight deck? Mission director. What information does the mission director need to know? In part, where the aircraft is going, how it will get there, and how the aircraft is performing compared to expectations. What is an effective way to impart this information to the pilot? Have the pilot direct the actions of the aircraft at the time of significant trajectory changes (e.g., transitions between legs, interception of an approach procedure). What are the problems and weaknesses associated with the pilot performing this task? Difficulty in achieving or maintaining precision, difficulty in remembering when to make the changes, and assuring a safe course of action should a nominal change be missed. How can automation assist the pilot in dealing with these weaknesses? The answer cannot be, have the automation fly the aircraft on a preprogrammed flight because then the pilot will not be 'doing it' at the time of execution. One solution is to use automation to adapt to the human's state of engagement in the task by dynamically allocating and deallocating tasks to the user based on their current state of engagement – i.e., a feedback loop (Prinzel, et al, 2000). However, this approach requires some way of monitoring the human's state of engagement (Pope has been successful in using EEG (Pope, Bogart, & Bartolome, 1995)).

Additionally, adaptive automation has the potential for confusing the user if inappropriately implemented because the user might not know what to expect from the automation. Rather than try and provide a near optimum state of engagement via adaptive automation, we suggest using a static allocation of human/automation tasks that will allow the user to be more consistently engaged throughout the flight. Our answer is to deal with the precision problem by having the pilot specify the high-level parameters and using the automation to maintain these parameters with precision, deal with the memory problem by providing reminders and alerts to the pilot to direct the high-level changes, and assisting the pilot in developing and executing a recovery plan in response to an error of omission. At face value this solution appears counter intuitive – if the machine knows that a turn needs to be made and knows how to make it, why not just have the machine make it? Because the human is removed from the task and is not as aware of what is happening than if he or she were involved in making the turn. Since the system is providing cues for speed and direction changes, isn't the human just becoming a 'meat servo' or 'monkey in the cockpit'? We would argue no. The human who has been involved in previous events is more likely to be situationally aware and to recognize a directive that is inappropriate than one who is just watching the automation. While this claim requires experimental validation, it is certainly intuitively sensible. In summary, one possible solution using the Complemation approach is to have the pilot make all high-level speed and direction changes in the aircraft and to have the automation make inner-loop corrections and act as a reminder to the human for making the changes. This design solution keeps the pilot engaged in the task in a meaningful way and that engagement reinforces situation awareness.

This approach appears to increase in-flight workload over the current automation approach. However, we believe that it serves to even out workload across the mission as opposed to the 'hours of boredom, moments of terror' workload profile. If the pilot had to perform all continuous control and stabilization tasks, the physical workload might be too intense. However, the number of high-level speed and direction changes during a mission is usually quite manageable. The famous Yerkes-Dodson law states that a moderate level of stress and activity improves human proficiency, whereas both high and low levels decrease proficiency. The 'hours of boredom and moments of terror' approach appears to operate in the low and high stress zones of least proficiency while skipping over the higher proficiency levels. While this approach should even-out physical workload to more desirable levels, additional design strategies may be required to address mental workload concerns.

5.2.1. Reducing Cognitive Distance rather than Workload **per se**

Modern automation has been found to shift the pilot's workload from the physical to the mental rather than reducing workload across the board (Wiener, 1988). Why is this true? We believe that it occurs for two primary reasons. One is that the pilot has an increased memory burden in that he or she must remember what the machine was programmed to do and how it will do it over long periods of time. The second reason is that the pilot must span a conceptual distance that Norman calls the gulf of execution and the gulf of evaluation (Norman & Draper, 1986). For example, if ATC gives the pilot a directive, the pilot must first translate that directive into a target that the automation will understand. Then the pilot must recall the programming steps necessary to enter that target into the flight management computer. These two steps are not part of the task of flying from A to B. They are entirely peculiar to the automation. The pilot knows what he or she wants to do and knows that the machine can do it. However there is a distance that must be crossed to translate what the pilot wants into what the automation needs to fulfill that command. This is called the Gulf of Execution. Similarly, once the flight management computer has been programmed, it can be difficult to determine if what the machine is programmed to do will actually fulfill the goal of the original directive. The pilot must translate what the machine is saying that it will do back into the language of the original directive. This translation is the Gulf of Evaluation. These mental translations and procedures do not have to do with the mission. They are a diversion along the path from goal to execution and back again.

One way to decrease mental workload without sacrificing situation awareness is to decrease the cognitive distance imposed by the automation on the gulfs of execution and evaluation (Schutte, 2000). One elegant approach to dramatically decreasing this distance is Riley's Cockpit Control Language (Riley et al., 1998) which allows the pilot to input ATC-like directives directly into the Autoflight system. The NFD will have as one of its design goals to remove as much machine/design induced cognitive distance as possible. Our goal is to have the pilot think about flying, not programming or getting the automation to work. Thus, the pilot will be more involved and engaged in the flight and mission itself than they would in more automated flight decks and yet will have lower physical and mental workload peaks.

5.2.2. Engagement as preparation for troubleshooting and back up

Another important benefit of increased pilot engagement in the flight is that it helps to reduce skill loss – a major issue if the pilot is called on to troubleshoot or act as a back up. In the event that some part of the automation or aircraft fails, the pilot will have a better understanding of what should happen because they have been involved in the task on many previous flights. For example, suppose some aspect of the guidance fails on approach. The pilot will have to depend on himself or ATC or some other form of guidance to assist him. However, he will know roughly what will need to be done because he has been involved with the task many times before. He can anticipate what the automation would have done if it were active. If guidance fails on a modern commercial aircraft, the pilot is left with an entirely different task (manually flying via the stick or wheel and column) as opposed to programming information into the FMS.

In addition, the pilot will have an additional opportunity to recognize and avoid mistakes. For example, if the pilot of a traditional FMS makes a mistake in programming the route such as entering in the wrong altitude for a waypoint that is several hours into the flight, he or she will be less likely to catch that mistake when the machine executes the altitude change. The machine will start the change and the pilot repeats the well-worn automation phrase – "What is it doing now?" They would have to troubleshoot to determine whether this is a problem and when they discover that it is, then they would have to correct it. If, as in the NFD design, the pilot is given a guidance cue to move the aircraft, he will have a chance to intervene before the action is taken. The question now becomes – "Why would I want to do that?" But the pilot would still be in control. In the automation example, the pilot has relinquished control for a period of time while they determine if there is a problem. This certainly will not guarantee that errors won't happen, but it will give the pilot additional opportunities to notice and address them before significant reductions in safety margins occur.

5.3. Artificial Intelligence and the Use of Metaphors in Interface Design

Shortening the cognitive distance in design is not a simple task. Computers do not reason in the same way humans do. The human brain is not just an organic digital computer. This is not to say that computers cannot be used to simulate brain-like and human-like behaviors, but the underlying logic and 'hardware' is fundamentally different. Modeling the activity of a single human neuron often requires a great deal of computer code – and as with all simulations, there are usually situations where the model fails to replicate the actual neuron. The point here is that creating artificial intelligence at the interface level, the conceptual model level, or at the neuronal level is extremely challenging. Thus being able to directly interpret a human's goals and desires is possible at best in limited situations and structured domains (especially at the levels of reliability required for certification on aircraft).

Fortunately, the aviation domain is relatively structured. The formal communication vocabulary is relatively small and the laws of operation (e.g., physical laws of aerodynamics and the airspace rules and regulations) are also fairly well defined and can be codified.

Many attempts have been made over the years to use artificial intelligence to interact more naturally with pilots with varied success (e.g., Pilot's Associate (Smith & Broadwell, 1986), Rotorcraft Pilot's Associate (Miller & Hannen, 1999), and CAMA (Onken, 1999)). We believe that the many of the limitations that these programs have encountered are largely due to applying an inappropriate metaphor for the interaction between the human and the machine, particularly in time-critical situations.

There are basically four types of interaction metaphors commonly used with artificial intelligence. The first is the human metaphor where the automation is modeled to be the equivalent of another person. This is the most frequently cited metaphor in artificial intelligence applications. The second and third metaphors are less common yet we believe that they have greater overall power in facilitating effective human-machine interaction in many situations. The second metaphor is that of a domesticated animal, e.g., a trained horse or trained dog. In this metaphor, the machine has intelligence and specialties but is not portrayed as the equal of a human. The third metaphor is the body metaphor where the machine is considered to be an extension of the body. The intelligence in the automation used in this metaphor is akin to that of the sub-conscious functions of the cerebellum, portions of the midbrain, brainstem, and central nervous system. The fourth metaphor is the tool metaphor that basically uses some human artifact that the pilot already has familiarity with to explain new functionality. Examples of tool metaphors are the desktop metaphor for computers (you manipulate files just like you would on a desktop) and the automobile metaphor for aircraft (flying an airplane is just like driving a car). Each of these metaphors will be briefly described along with some comments on their appropriate usage.

5.3.1. The Human Metaphor

The human metaphor as applied to artificial intelligence usually takes the form of an associate, assistant, agent, or employee. In the aviation domain they would replace the copilot or flight engineer or some other specialty on the mission. Indeed, in fully autonomous unmanned vehicles or autonomous wingman aircraft, these systems may replace the human pilot. Some associate systems are quite impressive in their ability to reason and communicate like a human. The human metaphor is usually the best metaphor to use when trying to interpret and understand the goals of the pilot and to communicate complex, abstracted, or conceptual information back to the pilot. One can express complex thoughts and goals to another human more easily than to a machine. Machines based on the human metaphor are often called on to provide knowledge-based reasoning, information, and behavior as opposed to skill-based behaviors. They often use natural language recognition and synthesis along with pictures and sounds to interact with the pilot just as a human would (humans do not come with keyboards!)

Of course, this metaphor is one of the most difficult to fully realize. In most cases only portions of human intelligence are emulated. What often occurs in these situations is the pilot assumes that the machine is either more intelligent or has a broader range of intelligence than it actually has. Humans tend to anthropomorphize even the simplest machines (Reeves & Nass, 2003) so machines that have human-like intelligence are easily anthropomorphized. The pilot may expect the machine to have common sense and know as much about him as he knows about the machine; and when the pilot expects or depends on something that is not within the machines capability there can be problems. Ultimately, the requirement for the pilot to understand and accommodate the machine's limitations translates into cognitive distance for the pilot. That is, the pilot must remember that while very human like in most ways, the machine does not have these other capabilities that a human normally would.

Thus, for the foreseeable future the best use of human metaphor type of artificial intelligence is in situations that do not require a great deal of breadth and depth and allow sufficient time for the pilot to work with the machine. In the aviation domain, these types of systems are best used in non-time critical tasks where the human can dedicate attention and concentration to the interaction. Thus, the human metaphor (that of an aid or assistant) is used in implementing the strategic and planning automation for the NFD.

5.3.2. The Domesticated Animal Metaphor

In this metaphor, the machine acts as an obedient animal. It can understand simple commands and it is highly depended on for its skill-based behaviors but not its knowledge-based behaviors. The domesticated animal metaphor chosen for the NFD is the horse or "H-metaphor" (Flemisch et al., 2003). The H-metaphor has several dimensions of particular relevance to vehicle automation. A horse is extremely adept at locomotion in various terrains and conditions such as running in close proximity to other horses. Similarly, a horse can avoid immediate hazards while continuing to support the rider's near-term objectives. It has a limited but flexible set of communication skills that can be used to direct a range of high-level or "loose rein" behaviors such as used in calf roping, and low-level or "tight rein" behaviors that provide nearly direct control over the horse's motions as used in dressage. The rider does not necessarily have intimate awareness of individual muscle movements or internal bodily activities of the horse.

There is generally a multi-modal interaction with a significant degree of physical, haptic contact that facilitates a largely subconscious, bi-directional communication link between the "wills" of the human and animal. This link is in many respects similar to the body metaphor described below, albeit between collaborative intelligences rather than within a single integrated intelligence. The haptic connection allows a rider to remain in contact with the "maneuver management automation" provided by the horse with little use of visual and cognitive resources. Short-term goals and behaviors can be efficiently communicated to the horse and the horse can contextually interpret and support these goals or recognize conflicts requiring modification of the goals. At the same time, horses rarely know the high-level goals or mission of their riders (except in TV and movies) and the human must give simple, frequent commands such as turn left, run, stop, jump and sidestep in order to achieve their mission. This is not to say that a machine based on the horse metaphor will not act autonomously. For example, a horse will instinctively avoid hazards or seek food if it is hungry. Furthermore, if there is no rider or the rider is incapacitated, the horse will return to its barn or the nearest safe area it can find. Finally, a horse may challenge the rider if his commands are perceived as dangerous.

In contrast to the human metaphor, the horse metaphor is well suited for machines that operate in time-critical and flight-critical situations. This is because the language set between the pilot and the horse is sufficiently small and because automation that performs horse-like behaviors (such as auto land systems) has already been certified. In addition, the horse metaphor is well suited for implementing the concepts described earlier in the Complemation section. The human gives high-level commands to the horse and the horse immediately carries them out. Again, horses that can carry out a long string of commands (e.g., 'go to the end of the block, turn left, travel for two miles, turn right …') are rarely found in the real world. Thus, the horse metaphor is used in implementing the automation for the real-time, tactical behaviors of the aircraft.

5.3.3. The Body Metaphor

The third metaphor places the machine as an extension of the pilot's body (either literally such as a robotic arm as an extension of the human's arm, or conceptually such as making the engine of an aircraft feel and react as if it were a body part). In the body metaphor, the machine enhances, empowers, and extends the human's abilities. The human applies their skill-based talents and behaviors and they are enhanced to superhuman capability. The intelligence associated with the body metaphor is similar to that of the cerebellum, certain parts of the mid-brain, brain stem, spinal cord, and autonomic nervous system. The machine based on the body metaphor offers the pilot faster and more precise reactions, greater sensing capability, an expanded range of capabilities, and greater strength. The pilot has a keen awareness of the configuration, fitness, and performance of their extended body and they have greater control over individual systems and effectors. In the horse metaphor, the pilot cannot command exact position of an aileron nor is the pilot able to directly sense the functioning of the engine in detail. In the body metaphor, the pilot can. Thus, the body metaphor is most useful when the pilot must apply his skills to the task at hand and must make tactical decisions with the overall strategy and goals constantly in mind. The body metaphor is described further in (Schutte, 1997).

The body metaphor is perhaps most useful for assisting the pilot in the back-up role. When the pilot is in the role of back up, it is likely that the workload level will be higher. Any assistance that the automation can provide in making the role of back-up as intuitive as possible is welcome. In these cases, the human may perform the machine's role best if he can get into its skin.

5.3.4. The Tool Metaphor

Tool metaphors in design have an advantage in that they are mapping some interaction or functionality from one artifact to another artifact. The original artifact is usually very simple (unlike the more complex living organism metaphors above) and therefore, easier to implement. That is, it is much easier to make a word processing program 'behave' like a typewriter than it is to have the word processor act like a secretary. Like the other metaphors, tool metaphors are very useful when the new system performs functions similar to those that the metaphor performs, such as the typewriter/word processor example. Where they are significantly different from the earlier metaphors is in that tools are rarely as general purpose as the organic metaphors. For example, if the human metaphor were used in designing and describing a word processor, it would not be difficult to also add a drawing function to the program. However if the typewriter metaphor is used, it is difficult to add the drawing functionality and continue to use the metaphor. It is very hard to draw using a typewriter. The designer would more than likely have to use a second tool metaphor (a pencil or brush) for the drawing task.

5.3.5. The Advantages of Using Metaphors in Design

There are several benefits in using metaphors in design. The first is that it provides some design guidance and boundaries for the designer. When the designer has a design choice he can consider how it would be handled in the appropriate metaphor. The designer can ask, "Is this consistent with what a horse would do, or what a person would do?"

Another major advantage is in training. Most humans have at least some experience interacting with humans, domesticated animals, their own bodies, and certain general tools. To a greater or lesser degree they know how to interact and what to expect out of that interaction. A significant amount of interaction and behavioral knowledge is already in place in the pilot's mind before beginning any training; significantly reducing training costs. To tell an *ab initio* pilot that the aircraft will respond to their commands in a way similar to a horse conveys a significant amount of information. The task for the trainer is then to fine tune that information so that the pilot fully understands what the system will or will not do.

5.3.6. The Dangers of Using Metaphors in Design

There are, of course, downsides to using metaphors in design. The first is that it may overly constrain the design. There may be a design feature available to the designer that would be highly beneficial and yet is inconsistent with the metaphor. For example, the use of voice communication from the system would be inconsistent if the system is designed using the domesticated animal metaphor. It is tempting and often quite appropriate or even necessary for the designer to depart from the metaphor in one or more aspects of the design. But that can lead to the second problem – inconsistencies with the metaphor. The classic example of this is the desktop metaphor in personal computers. The idea of storing files in a filing cabinet and in folders is extremely intuitive. So having a file system in a computer explained in terms of folders is very helpful for understanding how it works. However, the metaphor quickly breaks down when one considers that applications are also stored in the file cabinet in folders; one rarely stores a typewriter in a file cabinet. Similarly, on a real desk, when someone puts a piece of paper on the desktop, it is no longer in the file cabinet at that time. And when they change that piece of paper it remains changed even if the power goes off. But in the computer, when the user opens a document, it still exists in the file cabinet (the hard drive) and if the power goes off – all changes that weren't saved are lost. The user must 'unlearn' some of what they know about the interaction with the metaphorical system. This negative transfer can cause confusion – especially if the system is consistent with the metaphor in many other respects. Still another problem is that users can expect too much from a system that has been designed and trained using a metaphor. This often happens when the human metaphor is used and the user assumes that the system has some common sense greater than what it really has. Finally, a user can harbor negative memories regarding the metaphor source that may discourage their interaction. For example, if a pilot is told that the system behaves like a horse and their experience with horses has been that horses are temperamental, dangerous, or difficult to control they may be turned off to the system from the very beginning. All of these issues must be considered when using metaphors in design. If they are not, a valuable design asset can become a liability.

5.4. Actual (tactical) and Notional (strategic) behavior

As mentioned above, the NFD uses the Horse metaphor for aircraft's tactical behaviors and a human metaphor for the strategic behaviors. What is a tactical behavior and what is a strategic behavior and how do designers determine what tasks and functions belong in each category. While the terms "tactical" and "strategic" are generally understood by most people; they are very difficult to define. Often time or physical distance is used as a discriminator but the actual values for these discriminators vary greatly depending on context. Context elements that affect these discriminators are phase of flight, workload, urgency and threat, priority, and the type of task being performed. Another confusing factor has to do with deciding which task is being discussed. For example, the pilot, in cruise, decides to arrange for some maintenance after landing. He calls to the ground service center to arrange it. When the pilot is making this call, is he performing a tactical or a strategic behavior? It is strategic in that it has to do with activities relatively far in the future. But it is also tactical in that he is making the call right now (there may even be a sense of urgency regarding it – to reach an office before it closes). Many tasks have both tactical and strategic elements to them.

For the NFD, we have selected slightly different concepts that are more crisp and definable. Rather than discussing a behavior as tactical or strategic, we define it as Actual (doing) or Notional (planning to do or reviewing what was done). In addition, we add another element of the definition – the object being acted on. In this example, if the object of reference is the aircraft itself, it is clear that the call is a Notional behavior because nothing is actually happening to the aircraft. The call may affect what happens on the aircraft in the future but this is not guaranteed because there are so many possibilities. If the object of reference is the radio then the behavior is Actual because the pilot is actually using the radio – what he is doing is changing/affecting the radio.

When a person is planning a flight, he can be viewed as making an imaginary flight. The aircraft is a notional representation – not the actual aircraft. The aircraft might be represented by a pencil mark on a map (a notional representation of the earth and terrain) or ones and zeros in a computer. When the pilot moves this representation, the actual aircraft does not move. It is only its representative that moves. The definition of Actual and Notional can then be written succinctly as follows:

> **Reference Object**: the object that is being manipulated, being observed or is observing.
>
> ***Actual* Object**: a Reference Object that exists in the real world at the current time.
>
> ***Notional* Object**: a Reference Object that exists only as a representation of a real world object and is not the object itself.
>
> ***Actual* Manipulation**: manipulation of an *Actual* Object (i.e., a Reference Object that really exists in the real world.) Also known as *Actual* Control.
>
> ***Notional* Manipulation**: manipulation of a *Notional* Object (i.e., a Reference Object that is fictitious and only represents an object in the real world.) Also known as *Notional* Control.

The key aspect to this dichotomy is that nothing that is done to the Notional object will ever affect the Actual object. This is not the case in modern commercial transports where the Flight Management System (FMS) is often viewed as a strategic device while the "stick and rudder" and autopilot are viewed as tactical devices. If the autopilot is responding to commands from the FMS (i.e., coupled to the FMS), then inputs and changes in the FMS will affect what the aircraft does. If it is not fully coupled then those changes will not necessarily affect the aircraft. And there are a host of intermediate configurations where the changes may or may not affect the aircraft. The result of this ambiguity is often mode confusion, leading the pilot to ask the question, "What is the aircraft doing now?" or "Who is in control now?" The Actual/Notional distinction eliminates this confusion. There is one set of controls and interactions that cause the aircraft to move and these are the only controls that will cause it to move. When you or the automation manipulate these controls, they will move the aircraft (within physical limits, of course). There is a different set of controls for the Notional system and these will never affect the aircraft. There is no confusion regarding which system is controlling the aircraft – it is always and only the Actual system.

5.5. Roles, Engagement, Metaphors, and Behaviors: Tying it all together

When all of these theoretical concepts are combined, they lead to a consistent and robust human-machine interaction scheme. The pilot plans the flight aided by the Notional system. The Notional system interacts with the pilot using the pilot's terms and goals (not necessarily natural language). The Notional system insures that the route is safe and legal, and it is responsible for storing all of the planning, aircraft and airspace rules and procedures. The plan is then provided to the pilot and the Actual system as guidance for executing the flight. The pilot receives route and task guidance from the Actual system that includes a robust reminding and alerting capability. However, the Actual system normally does not move the aircraft autonomously based on that guidance[1]. The pilot must direct the aircraft to act using the H metaphor. In this interaction metaphor, the pilot nominally provides high-level directives (e.g., perform a standard takeoff/departure, following the indicated path) through the H-inspired multi-modal interaction or "H-mode". The H-inspired automation, or "H", reacts by interpreting the directives and providing the necessary inner-loop control actions. The pilot must actively engage during significant course/velocity changes since the H will simply continue its current behavior so long as safety is not an immediate concern. The H (based on the guidance provided by the Notional system plus any external directives such as from air traffic control) will provide robust alerting cues so that the pilot will not inadvertently miss a high-level change. If a planned or prescribed high-level change is missed, the H (after providing highly salient queries of the pilot) will assume that the pilot is not responding and will activate the self-preservation mode and 'fly back to the closest barn' while declaring an emergency to the surrounding airspace. Note, this does not imply that the aircraft will only fly along pre-planned routes—if the pilot wishes to deviate from a planned route for any reason (e.g., by "missing" change or simply maneuvering off the route), the H will not hinder this free maneuvering so long as the pilot positively responds to its queries, and the deviation does not create immediate safety concerns. In this free maneuvering mode, the H continues to provide envelope, conflict, and hazard protection but otherwise allows the pilot to maneuver the airplane.

During the flight, the Notional system, which created the plan using forecasted and predicted data, will constantly compare the predictions to real conditions or updated predictions. When there is a significant difference or change (e.g., weather cell moving faster or airport closure) the Notional system will signal the pilot that replanning is advised.

The Actual system must allow the pilot to efficiently make any near- term (tactical) actions using only the Actual displays and controls (i.e., not needing to use the Notional system). In current modern commercial transports, if the pilot has to make a runway change on approach, there is only one place that contains the language for achieving that – the FMS. The autopilot does not have any representation of runways. As will be described below, maneuvers such as changing runways using the Actual system are as simple and straightforward as changing lanes on the highway. In the NFD design, there is no need for the pilot to use the Notional system to assist in a tactical maneuver. There is no advantage whatsoever and therefore there is somewhat of a disadvantage to do so because it means that the pilot must interact with two

[1] The Horse or H may appear to be following the guidance when reacting to a safety threat. However this is coincidental in that the most logical and safe response happens to match the initial guidance. For example, if the aircraft has been cleared on an approach procedure in the terminal area and the pilot becomes incapacitated and is not commanding the aircraft, the H will not want to continue flying the last command given by the pilot because that might drive the aircraft into terrain and other traffic. The H will want to get on the ground. The safest way would be to follow the cleared path, but it is not doing so because of the guidance per se. Indeed, in this case, the H would be automatically declaring an emergency.

systems. Any advantage of using the Notional system for tactical control should be considered to be a failure of the design of the Actual system.

In this design concept, the pilot as mission director plans the mission and then has a role in executing it (figure 7). The pilot is a key link in both the planning loop and the execution loop. In most cases, the pilot is executing a plan that he created and thus this acts as a check on his own planning. A maneuver in a plan that made sense before the flight might not make sense at the point of execution. If for some reason the plan was incorrect or inconsistent with the pilot's goals and intent, there is a greater chance of him becoming aware of this discrepancy if he is involved in the execution. This awareness supports the pilot's role as troubleshooter in that he is 'spooled up' with the situation when an anomaly occurs. Situation awareness is one of the most important factors in decision making (Klein et al., 1993) and supports the pilot in making good troubleshooting decisions. If some aspect of the primary mission (e.g., guidance, H feedback, H control, Notional system) should fail or become degraded in flight, the pilot will have been actively involved in those decisions and will have observed the automation's role repetitively in normal operations such that he can take on that role with moderate success if needed. Thus the back up role is supported. There are other aspects of the design that support these roles that are not discussed in this section (e.g., mission status graphics, communication Complemation, on-line information and instruction information) but will be discussed later in the document.

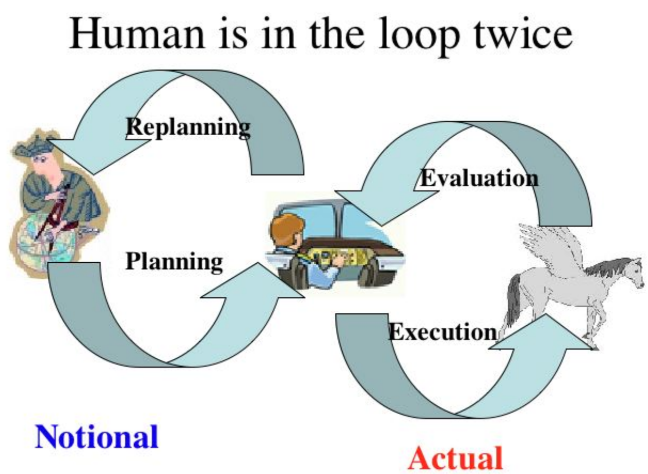

Figure 7: Dual role of the pilot assists in error prevention

6. NFD Components

In this section, the major components of the NFD system are described. First, the functional roles and responsibilities of the pilot and the aircraft, including its automation, are developed. Each function has its own information, action, authority, and responsibility requirements. For the aircraft, these functional requirements are implemented via the two major interface system segments, the Actual and Notional Systems. As discussed previously, this separation is intended to simplify the pilot's task of maintaining a useful level of situation awareness and avoidance of mode confusion. The Actual and Notional systems are described in sections 6.2 and 6.3 respectively.

6.1. Assumptions

Currently, there is a great deal of research and development in the aviation domain. Technologies such as data link systems, synthetic vision systems, advanced sensing instrumentation, graphical weather information systems, self-separation systems, and automated safety systems. In addition, there are several potential airspace innovations on the horizon (e.g., NEXTGEN and its potential elements such as DAG-TM and 4D RNP). The NFD concept will make use of all these technological innovations when possible and needed. And the NFD concept will be adaptable to current as well as potential new airspace concepts and rules. Perhaps more importantly, the NFD will provide a framework in which new and unforeseen technologies can be inserted in a consistent manner so that the pilot-machine interaction is consistent with the rest of the pilot's interaction experience.

6.2. Roles and Responsibilities

Functions are allocated to the pilot first since humans are less designable than machines, then the automation, and to other services based on the roles that they are assigned in the flight deck. Palmer et al. (1994) describe roles that must be considered for both the human and the automation when designing human/machine systems. For the human, these roles are team member, commander, individual pilot, and occupant. They are defined as follows:

- Pilots as *Team Members*: This reflects the role of pilots as members of a team that includes not only the other flight crew members, but also elements of the flight deck automation, and in the larger context, elements of a distributed system including air traffic controllers, airline dispatch, regulatory agencies, etc. The issues involved include the need for communication, coordination, and shared functional understanding among all team members to successfully accomplish tasks.
- Pilots as *Commanders*: This reflects the role of each pilot, individually, as being directly responsible for the success of the mission. The issues involved include the level of pilot authority over the flight deck automation, and the ability of the pilot to delegate tasks.
- Pilots as *Individual Pilots*: This reflects the role of pilots as individual human pilots working within a complex system of controls and displays. The issues involved include many of the traditional human factors disciplines such as anthropometrics, control/display compatibility, and cognitive processing.
- Pilots as *Occupants*: This reflects the role of the pilots as living organisms within the flight deck environment. The issues involved include ingress and egress capability, protection from the radiation and atmospheric conditions at the expected cruise altitudes, and accommodation of items such as food and drink containers. (Palmer et al., 1994)

We expand on these definitions in the following ways. The role of Commander is defined explicitly in terms of the mission and is thus called Mission director. The role of Individual Pilot is made more explicit by defining what the pilot should be responsible for – in this case, Troubleshooter and Back-up.

For the automation, Palmer et al. (1994) define roles more in terms of levels of automation, calling on the automation to perform one of the following roles: Substitute, Augmenter, and Aid. In the substitute role, the automation replaces a function that the human would normally perform (e.g., autopilot). In the augmenter role, the automation provides active assistance to the pilot's actions (e.g., yaw dampers, envelope protection). In the aid role, the automation provides information collection, integration, and presentation.

For the NFD, we are more explicit with regard to what the airplane and automation will be doing with respect to the mission rather than simply describe what level of automation will be used. The roles are Planning Assistant, Trajectory Manager, Systems Manager, Monitor, Back-up, and Team member. In general, these roles relate to the Palmer et al. definitions in the following way: Planning Assistant – Aid, Trajectory Manager – Augmenter, Systems Manager – Substitute, Monitor – Substitute, Back-up –

Substitute, and Team Member – Augmenter.

6.2.1. Pilot

The NFD strives to maintain and encourage essential aviation skills for the pilot. A pilot of an NFD equipped aircraft is expected to understand the fundamental factors of flight and airspace operations and to be proficient in their use and application. The pilot must be an active part of the aircraft's operation and must have the knowledge, information, and authority to be responsible for the aircraft. This makes design difficult when an equally important goal is ease of use. If the normal operations of the vehicle are extremely simple (e.g., the pilot says, "Take me to my Grandmother's house."), the pilot will not be able to intelligently respond should something go wrong. The pilot may have learned the fundamentals of flight in order to get his pilot's license but that knowledge is likely to atrophy if not routinely used. How does a designer balance maintaining the pilot's necessary skill set, while not requiring all pilots to be part of the elite few with the 'right stuff'? The answer is to explicitly state the roles and responsibilities for the pilot and then design to support those roles and automate functions that do not support those roles. In the case of the NFD, the following roles were selected.

6.2.1.1. Mission director

In general, the mission means safely getting people and/or cargo from point A to point B within certain time, cost and comfort constraints. Therefore, in the role of mission director, the pilot needs to monitor these constraints and influence them. In general this means observing the mission level attributes of the flight such as time, fuel, location, expected time of arrival, etc. However, other factors can impact the successful completion of the mission even though they might be considered systems (engine performance, electrical load, etc.) or trajectory (lift, drag, thrust, heading, track, etc.) attributes. The mission director must be aware of these factors even if he is not able to do anything about them because they can affect the quality of his mission decisions. For example, degraded engine performance because of a fouled spark plug might lead to a different mission response than degraded engine performance due to low oil pressure.

A large part of directing a mission is monitoring the progress of the mission. Because diligent monitoring is not a human forte, the machine should not just allow but must actively encourage the human to monitor these factors. Often, designers assume that since the information is available to the pilot that the monitoring requirement is fulfilled. However, human pilots can easily become complacent when monitoring highly reliable systems or for infrequent events (Parasuraman et al., 1996). A possible approach is to call on the pilot to perform a task that requires that the pilot use certain information. This requires the machine to know what the correct response should be and then have access to the sensor and situational data from which to make a comparison. The machine must constantly monitor that data and alert the pilot when there is a discrepancy. Such discrepancy information is extremely valuable in the pilot's decision-making process (Klein et al., 1993).

6.2.1.2. Troubleshooter

One of the primary roles for the human in a highly reliable system is to troubleshoot when things go wrong. The human has a unique abilities not found in computers. Humans "are excellent detectors of signals in the midst of noise, they can reason effectively in the face of uncertainty, and they are capable of abstraction and conceptual organization," (Billings, 1997). These abilities are especially important when something has gone wrong or is simply unusual. Humans are better equipped than automation at dealing with the unexpected or unanticipated. But the fact that humans are better at troubleshooting than automation does not imply that they are especially good at it. They require a great deal of support. In order to deal with the unexpected in a timely manner, they must be aware of the situation. If they are in a highly reliable, highly automated, and preprogrammed environment, they are more likely to be 'out of the loop' or complacent when an abnormality occurs. This situation sets the human up for failure at the troubleshooting task. The human must be engaged in the mission at all times and the best way to insure that is to provide active involvement in the mission.

In order to effectively troubleshoot, the human pilot needs to evaluate the outcome of any responses to an abnormality. This can require that the human track a number of variables and constraints. These variables and constraints may be interdependent and their interactions may be complex. Humans have difficulty in mentally tracking all of these variables and interdependencies. Humans should be aided (ranging from memory aids to simulation environments that can test theories and responses) to maintain this information and to determine the consequences of any proposed response.

Since the situation that the human will probably encounter in the course of troubleshooting will likely be unanticipated, it is important that the human be trained regarding how to troubleshoot. This training will likely involve meta-procedures (i.e., what to do when there are no written procedures applicable to the current situation) that describe methods for troubleshooting rather than specific steps. For low-time or low training pilots, troubleshooting assistance may be provided on-line. However, the on-line troubleshooter will have to be able to quickly immerse themselves in the mission.

6.2.1.3. Back-up

In the case of some automation failure or even a mechanical failure, the human pilot may be called upon to perform a duty normally performed by the machine. For example, automatic communications may not be functioning and the human would have to communicate with airspace and ground services using voice radio. Similarly, the flight planning automation may not be functioning and the human must take on the responsibilities for planning, replanning and monitoring the flight plan. In rare cases, there may be 'manual reversion' mode where the human must take over some more mechanical duty normally performed by the automation. For example, the pilot may have to manually lower the gear, or may have to control the trajectory of the aircraft without automation assistance.

These events will most likely be very rare – a pilot may see such an event only once in their lifetime. The pilot should not be expected to maintain information and proficiency in these back-up roles. They should either be reinforced by training or by what Billings refers to as Information and Management Automation (Billings, 1997). That is, there should be salient, accessible, and intuitive resources that aid the pilot in remembering how to perform the back up duty.

In addition, because the pilot's workload has increased when they perform this back-up duty, the system should provide additional monitoring and assistance for the normal duties of the pilot. The pilot may become engaged in the backup duty to the neglect of a normal task such as mission director. The design should support the pilot in the role of mission director, even if it means that the pilot may become less involved in the direction of the mission. It is in these conditions that the automation is used more extensively.

6.2.1.4. Team member

The pilot must cooperate with the automation. Cooperation requires communication skills and conflict management skills. The pilot must know how to communicate his intent to the automation and must be able to evaluate the automation's intent (i.e., Norman's Gulfs of Execution and Evaluation (Norman &

Draper, 1986)). The pilot needs to be able to monitor the automation‘s performance. This is a particularly difficult problem in that the pilot must monitor the automation without the assistance of the automation, since that assistance may be the part of the automation that is defective. The only way to help the pilot perform this monitoring/cross-checking task is to make the intentions and the performance of the automation extremely noticeable and obvious.

In some cases, the assessment or intent of the pilot may conflict with the assessment or intent of the automation. A general design principle that is commonly used is always to defer to the judgment of the pilot. However, if the pilot has not been given sufficient information and sufficient engagement in that information, the pilot may default to the judgment of the automation – thus losing the value of the pilot's intelligence. One way of addressing this problem is to foster and encourage collaboration between human and machine. The idea is that the more that they work together, the more acquainted the human will be with the performance of the machine. It may even be possible for the machine to adapt to the human over time – to learn routines and patterns of a particular pilot's behavior.

6.2.1.5. Occupant

The pilot is not a machine and cannot be treated as such. There are obvious considerations such as readability of displays, reach and strength issues, and allowing for eating and drinking, stretching, rest, and lavatory breaks. However, humans have other considerations that are often overlooked in design. Humans are prone to boredom, habituation, daydreaming, tunneling, complacency, over reliance, and curiosity. These are not errors or faults, but survival traits. They must be expected and accommodated. Humans require some sort of emotional ergonomics that makes the pilot feel relaxed, involved, important, and in control. This means that the pilot must be allowed some down time periodically and the he must be meaningfully involved in the task as opposed to busy work (Billings, 1997).

6.2.2. Airplane & Automation

The roles defined above for the pilot define the role of the automation. Put simply, the airplane must do everything necessary to maintain operational safety and efficiency that the pilot is not doing. The airplane is expected to do everything that the pilot isn't expected to do or cannot do due to their finite resources. This creates non-traditional roles for the automation and perhaps more importantly, non-traditional certification requirements. For the NFD, one prominent change is to certify elements of the trajectory manager (i.e., the H-mode or autopilot features) to a higher level of reliability than autopilots are currently certified in modern commercial aircraft. This has been done in more limited applications (as in the case of CAT III-C autoland) so it does not require significant technological breakthroughs. Similarly, the automation must take on a more prominent role in checking that the aircraft and the mission are in compliance with airspace rules and regulations. In doing so, some liability will be transferred from the pilot to the manufacturer and to government authorities. This represents a major change in design, however given the goals of the NFD, it is simply unconscionable to demand that the pilot maintain such a huge database of information in their memory (the Federal Aviation Regulations / Airman's Information Manual (FAR/AIM) alone consists of over 300 pages of regulations, procedures, and charts) or that they have to perform an exhaustive search of all applicable regulations before each flight. Therefore, much of the responsibility for insuring that a given plan is in compliance with quantitative legal requirements should be placed on the automation. In addition, the burden of informing the pilot of aspects of marginal or non-compliance is also placed on the automation.

6.2.2.1. Planning Assistant

The planning assistant is an information aid to the mission director. In the NFD, this is normally (but still remains a research issue) performed by the Integrated Trip Planner. The planning assistant performs the route calculations, optimizations, alternates and options that are legal[2], feasible and safe. The planning assistant then creates a plan for the mission director to follow. This plan takes the form of a task list where each task is triggered by some event (e.g., time, location, configuration). The planning assistant notifies the pilot when those tasks are eminent, due, and past due. The pilot can modify that plan and the planning assistant will continue to assure that it is legal, feasible and safe. The planning assistant can be used to record non-trajectory related tasks (e.g., communication tasks). The plan, once created and checked, can be electronically communicated to the Actual system to be used as guidance (not control).

The planning assistant also monitors the status of the plan during flight, to identify when there has been a significant change (e.g., a weather cell moving faster than predicted, an airport closure, a new temporary flight restriction) and alerts the pilot to this change as a potential need to replan. The assistant then provides alternatives to the pilot or allows the pilot to create his own.

6.2.2.2. Trajectory Manager

In general, the trajectory manager is responsible for the safe and successful accomplishment of short-term tactical maneuvers. This usually means holding the aircraft on the current trajectory, preparing for the next change in trajectory, accomplishing that change, and establishing a new trajectory. In some cases, the change from one trajectory to another is complex or requires many configuration changes (e.g., flaps, gear, engine adjustments) over a short period of time, such as landing, takeoff, and flying a holding pattern in the air. In these cases, the trajectory manager may have to accomplish many trajectory changes rapidly. These patterns of complex trajectory changes are chunked into a single command called a *behavior*. The Trajectory Manager carries the primary responsibilities for the successful short-term (tactical) planning, assessment and execution of aircraft trajectory segments. These trajectory segments can be pieced together by the mission director (the pilot) to complete the mission. The automation will be responsible for smooth transitions where possible between segments. The trajectory manager must be highly skilled at performing maneuvers and must be able to react quickly to threats. This requires a thorough awareness of the immediate environment.

The trajectory manager must monitor the environment at a high frequency. Air data, position data (e.g., inertial reference system, global positioning information), radar, ADS-B, machine vision, weather information and any other available information can potentially be useful to the trajectory manager. In the Naturalistic Flight Deck Concept, the trajectory manager is implemented using the H-metaphor. Just as a horse can negotiate terrain and implement the high-level commands from the rider, the H-mode as trajectory manager can implement the commands provided by the pilot as mission director.

The trajectory manager accepts goals from the mission director and translates them into trajectory goals that are then passed on to the systems manager. While the trajectory manager does not 'know' how the systems work, it does know the capability of the systems in fulfilling trajectory goals. For example, it knows the maximum thrust that can be produced by the engines but doesn't know whether the engine is a turbo jet or turboprop engine. After passing the goals down to the systems manager, the trajectory manager looks to determine if the goals are being achieved. If the trajectory manager cannot achieve the

[2] Legal here means that the planned route is in compliance with quantitatively defined regulations and airspace limitations. It is important to note that the plan is notional and in no way guarantees that the pilot must adhere to it. Thus the pilot can violate the plan and potentially perform an illegal action.

goals that the mission director has set for it, then it must notify the mission director that the goals cannot be met and provide explanations and alternatives.

6.2.2.3. Systems Manager

Systems on modern aircraft are extremely complex. Many systems are interconnected and this further adds to the complexity. It is highly unlikely that the human can maintain an understanding of how the aircraft systems work without providing a great deal of training to the human. In addition, there may be differences from aircraft to aircraft regarding how systems are implemented. It would be unreasonable to demand that the human understand these differences.

The systems manager is responsible for configuring the aircraft systems to support both the trajectory and mission requirements. It must monitor the performance of the systems and determine when there is an abnormality or disparity between how they are performing and how they are expected to perform. This requires that the systems manager have a reasonable model of the normal operation of the aircraft systems. The systems manager must also be able to translate commands and goals from the mission director and the trajectory manager into systems and configuration commands. Similarly, the systems manager must be able to translate the impact of system configurations and malfunctions to the trajectory managers and mission directors in terms of their goals and objectives.

The systems manager must be able to describe the operation and the interconnections of the aircraft systems to the pilot in real-time, should the pilot have to troubleshoot or intervene (taking corrective action or acting as a back up.) The systems manager should make it very plain as to where the pilot can intervene.

6.2.2.4. Monitor

Humans simply are not good monitors of highly reliable systems or infrequent events. They become complacent and can become less sensitive to true signals over time. Machines do not suffer from this flaw and therefore a majority of the monitoring responsibility is placed on the machine. The machine monitors the environment, the progress of the mission, the legality and feasibility of the mission, the state of the aircraft, and the state of the crew. The automation monitors for both mission effectiveness and efficiency as well as for safety. In general, if the monitor detects an abnormality that will affect the mission, trajectory, or systems effectiveness, the respective manager (i.e., mission, trajectory, or systems) will be notified. If safety is threatened by an abnormality, then the human is notified as well as the manager. In some cases, the Back-up may be engaged.

6.2.2.5. Back-up

The back-up role for the automation has two flavors. The first is a safety back-up. The safety back up is engaged if the automation determines that the human is not fulfilling (or violating) his role as mission director and jeopardizing the safety of the vehicle. An example of this is when the H-mode determines that the human is incapacitated and then aborts the mission per se and pursues a safe state (e.g., landing at the nearest suitable airport). The second form of back-up occurs when the human is called upon to perform a trajectory or systems related task (e.g., when he has to act as back-up). In these cases, the automation should attempt to perform some part or all of the duties that the human is now neglecting. For example, suppose that the pilot has to perform navigation duties normally performed by the planning assistant. If the pilot is normally responsible for initiating commands to the trajectory system based on the flight plan, the trajectory system may execute these commands by itself with permission from the pilot. The trajectory system would notify the pilot that it was doing so and offer ample to opportunity for the human to intervene.

6.2.2.6. Team member

Automation is often described as the strong silent type (Woods, 1996). It does what it does and rarely informs the crew of why or sometimes even what it is doing. Such automation does not make for a good team member. In the naturalistic flight deck, the automation must be more revealing. It must let the pilot know when it is approaching its limits. If the pilot requests it to do something that it either cannot do or infers is unwise to do, the automation must be able to explain why and provide options for achieving the higher level goal of the pilot. The automation should be required to understand the pilot's vocabulary (not necessarily natural language) and must communicate in terms of the pilot's goals rather than the machine's operation. Another way of describing this is that the pilot should not have to know how to program the computer. The pilot should just know how to achieve the mission. Then the machine must be able to state its intentions, status, and prognosis in terms that the pilot will understand, rather than make the pilot translate from the machine status to mission goals.

6.3. Actual System

As described in chapter 5, the Actual system provides access to information and control functions relevant to the immediate flight situation and actions of the aircraft. The "time horizon" of information needed to assess the immediate situation should generally project far enough out to assess factors that might necessitate or constrain temporary deviations from the nominal route (e.g., local traffic, weather, terrain, aircraft health/status), any imminent pre-planned high-level changes in the route, and potential, urgent contingencies such as a forced landing or escape routes if operating in conditions conducive to hazardous weather (e.g., icing, thunderstorms). Through the Actual System, the pilot should be able to efficiently assess and implement any tactical air traffic control (ATC) directives or perform self-separation as appropriate. There are several key elements that allow the Actual system to perform reliably, predictably, and efficiently. The major subsystems within the Actual System relate to the automation implementing horse-like transportation capability and interaction, robust task management and alerting, autonomic systems management, and communications. These elements are described below.

6.3.1. H-system:

The H-system, the physical realization of the H-metaphor in the NFD, is shown conceptually in figure 8. The H-system can perform complex behaviors such as trajectory following, landings, take–offs, and holding patterns as a single behavioral entity. For example, the pilot can direct the aircraft to land on a particular runway and it will take care of lining up on the runway and maintaining proper glide slope. While the H is performing these behaviors, the pilot can continuously control key parameters such the runway aim point of the approach path. Using real-time and stored information (e.g., terrain, airspace databases), the H-system formulates an assessment of the current situation using a simple, object-oriented model structure accommodating the common factors of flight including weather, terrain, traffic, airspace elements, own ship performance, and pilot directives. In this formulation, the H identifies hazards that must be avoided, lesser conflicts that should be resolved and positive features that it should move toward like the nominal route from the Notional System or a runway designated by the pilot. The H-system develops a nominal course of action including a flight path based on this assessment. The general priorities in developing this course of action reflect: 1. Self-preservation, 2. Any real-time directions from the pilot, 3. Satisfying regulatory requirements, and 4. Following nominal route segments from the Notional system. The pilot is able to intuitively observe and influence the H's situation assessment and action formulation process through the H-mode interface element, described in more detail below. The interface also allows the pilot to easily override these processes if desired or if required, for example, in response to erroneous information.

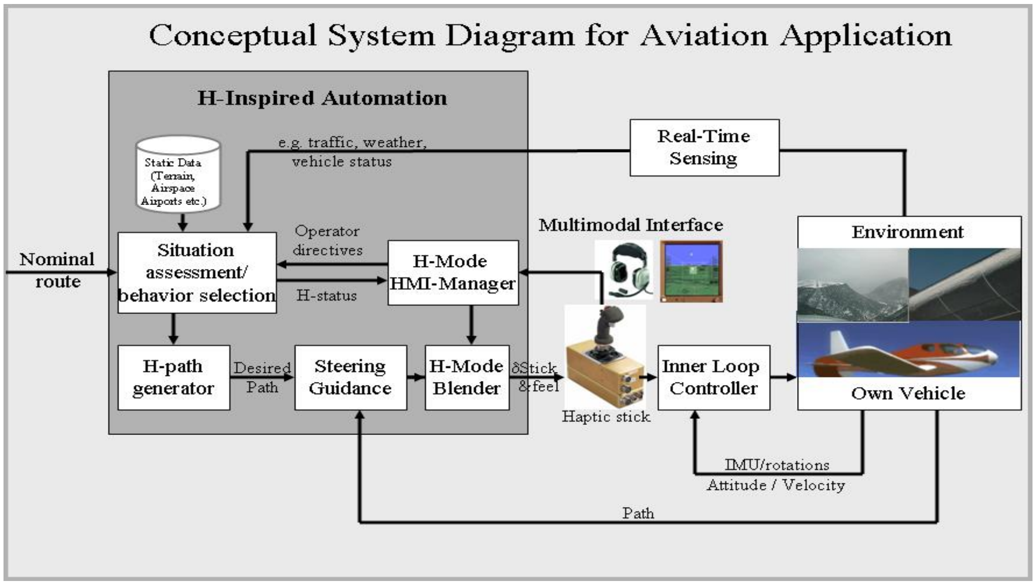

Figure 8: H-inspired flight control system

The pilot manages the vehicle's trajectory and maneuver behaviors through the H-mode interface system. The generic interaction characteristics of the H-mode are compared to conventionally automated vehicles and non-automated vehicles in table 3. The H-mode characteristics should support more natural communication between the pilot and automation. The implementation concept includes a synthetic-vision based primary flight display (PFD), a tactical navigation display (TND), two-way auditory communication, and the haptic side-stick and speed command lever (not shown in figure 8).

	Vehicle class		
Characteristics of the interaction	**Conventional vehicle** (w/o control automation, e.g. 20th century car without cruise control)	**Conventionally automated vehicle** (e.g. 20th century commercial aircraft)	**Horse / H-inspired vehicle**
Direction	Mainly unidirectional	Mainly unidirectional, some bi-directional	Mainly bi-directional
Coding	Analog / spatial	Mostly linguistic /abstract Some analog / spatial	Mostly analog /spatial, Some linguistic /abstract
Modality	Multimodal with haptic component	Strong visual component, some multimodal aspects	Multimodal with strong haptic component
Discrete or continuous?	Mostly continuous input	More discrete input and output	Mix of continuous and discrete input / output
Importance of visual modality for the guidance task	High	High	Medium
Redundancy in the interaction	Low	Medium	High
Negotiation of different wills	None	Non-overt, brittle, "either / or" (automation will is more implicit)	Transparent, fluid ("automation" will is explicit)
Who is in the physical loop, human and automation?	Human (automation only in low level functions, e.g. a governor in a car)	Exclusive either/or for specific axes	"Automation" and human are in the loop simultaneously

Table 3: Comparison of H-inspired vehicles to more traditional vehicles

The haptic modality provides the primary link between the pilot and flight control automation. Both the pilot and the higher-level functions of the H control the path of the airplane through the haptic interface devices. The position outputs of these devices are the inputs to an inner-loop stability and control augmentations system (SCAS). The SCAS provides a velocity-vector based response type with integrated flight envelope protection and is analogous to a horse's cerebellum and neuromuscular systems, providing an interface between higher-level, cognitive processes and low-level sensors and actuators. The SCAS provides both the pilot and the higher-level functions of the H, with simple, direct control over the immediate motions of the airplane. With the other, higher functions of the H disabled, the feel characteristics of the stick and response of the airplane are identical to current fly-by-wire aircraft with a velocity-vector based response type such as described by Duerksen (2003). The H also implements its higher-level behaviors by moving these same devices. The H accomplishes this by commanding their zero-force or trim positions. If for example, the H is following a trajectory segment, the path steering function will manipulate the stick position such that the airplane captures and tracks the desired path. The pilot can feel the actions of the H by lightly holding onto the controls. If the pilot applies a force to the stick while the H is maneuvering, the stick position will move from its zero-force position by an amount dependent on its feel characteristics such as the break-out forces and centering gradient. The H's interaction manager monitors the pilot's forces and uses this information, combined with its overall situation assessment to determine short-term directives from the pilot and adjusts its actions in accordance with these directives. The interaction manager also can adjust the force-feel characteristics of the controls so that the pilot can feel limits or reservations that the H may have in responding. In addition to these low-frequency, continuous force signals, both the pilot and H can send and receive high-frequency, "language" elements via the haptic controls. These elements include a simple but flexible set of shakes and pulses that enable basic communication of discrete commands and signals to be communicated.

The combination of continuous and discrete language elements allow the human and H to be "in-the-loop" simultaneously and as shown in figure 9, fluidly exchange roles as leader and follower as needed or desired. When the H has the lead, the situation is termed "loose reins" and the H typically has a well-defined behavior such as following a procedure, taking-off or landing. The pilot's hand rides lightly on the controls and can provide gentle cues that modify the H's performance within the current behavior. Example modifications would be tracking slightly above the glideslope or to the left of a centerline, following traffic with closer than nominal separation, or landing long. In "tight reins", the pilot has the lead and H minimizes its use of cues except as needed to support hazard awareness/avoidance or facilitate haptic communication.

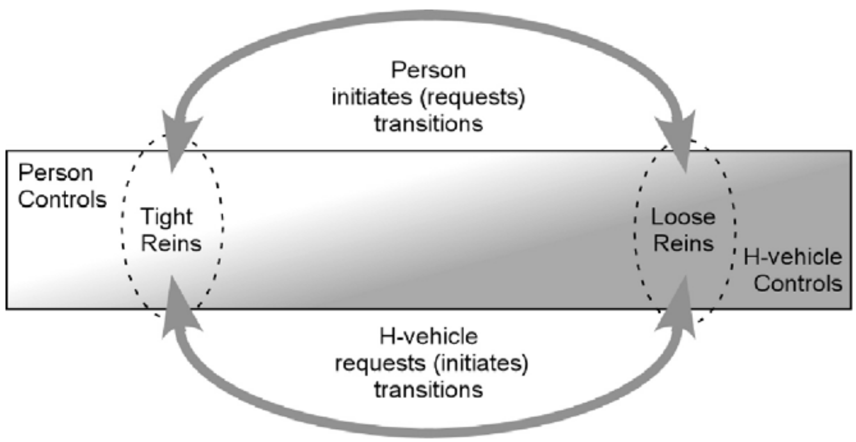

Figure 9: Potential transitions in an H-Mode

The two visual displays provide graphically intuitive representations of the external environment overlaid by basic flight parameters and the H's interpretation of this information. Since the H performs the inner-loop, attitude stabilization and control functions, the presentation of flight parameters can be significantly simpler than current displays. The environmental information includes physical elements such as terrain, weather, and traffic and virtual elements such as airspace boundaries and published fixes, routes, and procedures. The route from the Notional system, if present, is also included. Symbology specific to the H includes the H's situation representation, the "H-path" and the H's center of attention (H-coa). The H's situation representation provides a picture of how the H perceives the external environment. This presentation allows a pilot to quickly ascertain what the H is responding to, how these influences are shaping its actions and how it would respond to inputs from the pilot. The H-path represents the path that the H will follow on its own without further short-term, pilot inputs. The H-coa allows the pilot to graphically program the H to perform multi-step behaviors such as flying to a fix or intercepting a procedure. The H-coa is a narrow cone around the aircraft's current velocity vector and appears as a circular reticle on the perspective display and a beam emanating from the nose of the own ship symbol on the map display. When the pilot maneuvers the airplane such that a fix or route is steadied (or aimed) within the H-coa symbol, the H highlights the feature and generates a list of situationally appropriate actions. If the pilot accepts one of the actions, it becomes active and the H can transition to loose-reins. While this sounds complex, in operation it's quite natural. For example, to change between parallel approach procedures, the pilot simple uses the stick to maneuver the airplane toward the parallel procedure depicted on the displays. The H displays a proposed path that intercepts the procedure. By accepting this path, the change is complete. In addition to this "point to program" capability, the pilot can also couple the automation to a route or procedure by simply flying the plane into position and alignment with the desired procedure as shown on the visual displays. The auditory interface features will compliment the haptic and visual elements. In keeping with the H-metaphor, these communications can be bi-directional but limited in content and complexity (e.g., not complex sentences).

6.3.2. Task Management and Alerting:

Another aspect of the Actual System and H-mode interface is a task management and alerting capability. Human memory (both retrospective and prospective) is a volatile and unpredictable part of human behavior. Because the pilot is required to be more engaged in the mission in the NFD, there is a potential for errors due to human memory problems (e.g., forgetting to level off at a certain altitude, forgetting to contact ATC, forgetting to reconfigure systems). The concept of complemation calls for the automation to assist the human in dealing with these problems. As part of the Actual system, the pilot will receive visual, haptic and auditory cues that prepare them for these actions and as well as recommend or take corrective action if an oversight takes place. Clearly the design of this capability must address complacency concerns to ensure that the pilot does not become reliant on this capability for routine operations. The intent of the system is to encourage the pilot to function as an independent agent, not a 'meat-servo' that only responds only to direct cues for action. In addition, the design of this system must strive to eliminate nuisance alerts.

The pilot may only be able to concentrate on one task at a time and is likely to become absorbed in a task to the neglect of other monitoring duties. While this concentration is appropriate for problem solving and resolution, it is inappropriate for monitoring the situation of the aircraft (Schutte & Trujillo, 1996). Rather than have the pilot switch attention for the monitoring task, the system can provide mission status in the pilot's 'periphery'. The NFD will use concepts such as Mission Status Graphics (Trujillo, 2002) and ubiquitous, ambient cues such as background sound and display border coloring to provide situation awareness to the crew while concentrating on a particular task.

6.3.3. Autonomic Systems Management:

In general, most of the systems management on board the aircraft will be performed by the automation. Details and complexities of the hardware and design are often too difficult for the average and infrequent pilot to hold in their mind for long periods of time. In addition, most configuration changes (e.g., gear and flap deployment) are handled automatically by the machine. However, this does not mean that the information about the system's performance is kept from the pilot. Rather, system status, diagnosis, and prognosis information is presented to the pilot along with their consequences on the mission of the aircraft. Even if the pilot cannot affect the system in any way, the information can help the pilot make informed decisions regarding the mission (such as whether to divert to an alternate, whether to choose one alternate over another).

Systems management also encompasses the human and the automation. These two represent the intelligence of the mission and are crucial to its safety and success. Human monitoring has been briefly touched on in the discussion of the H-mode above. But more elaborate monitoring of the human may take place as technology improves. For example, blood alcohol levels, blood sugar levels, brain activity, etc. If the human is suffering from low blood oxygen or blood sugar, their decision-making ability could be impaired. In addition, the automation must be monitored. Monitoring the automation should be delegated to the pilot because he is the most obvious agent to perform crosschecking. However, humans are poor long term monitors of highly reliable equipment. Therefore the automation must not only be designed to fail safe but also to fail loud so that the pilot is aware of its failure. Of course, one of the major dangers is the subtle automation failure, one that can easily go undetected. It is important for the automation to provide the pilot with some status of its own activities and health if possible. The pilot will need to be trained to detect abnormalities in this information. If the automation has failed and that failure is not obvious to the pilot, it most likely will be overlooked.

6.3.4. Communication:

Another crucial part performed by the Actual System is communicating data with multiple and various sources of information. The formats of these sources may be digital or verbal. The system must have an internal data format that allows it to integrate information but must be able to interpret ATIS, NOTAM, PIREP, NEXRAD, and other such data and translate it into the form useable by other elements of the system such as the H-system and the Notional System. The format and the data available may be location dependent (for example, in Asia or Latin America). The communications element must be able to handle these data types as well, or know the boundaries of the area in which it can operate. Finally, the communication system will be able to transmit information to other information services, for example, to file a flight plan with the local airspace authorities, or to request facilities at the destination airport. The origin of this information may be from other system segments such as the H-system.

A key challenge in the near term is assisting the pilot with voice based ATC interactions. While voice communication may, at some point in the future, be completely replaced by data link for all routine ATC exchanges, this transition is likely to be slow and the reality of voice communication must be recognized. Voice communication raises two related issues. The first is correctly receiving and sending clearances and clearance requests. The second is entering the clearance into the automation. The NFD will provide ground to aircraft communications in a consistent, redundant presentation of information. If the information is transmitted by datalink, then the system will present the text information to the pilot. In addition to this text information, a voice synthesis program will speak the information to the pilot if the pilot so chooses. Conversely, if the information from the ground is transmitted over voice channels, a speech recognition system will attempt to recognize that information and provide it in a text format as well. So in all cases, the pilot has the option of either hearing the information or seeing the information or both. There are several advantages to this approach. The first is that humans understand and remember information that is presented both visually and aurally together better than either medium alone. Second, it provides a consistency in whatever airspace the pilot may be flying. Third, it allows a mechanism for the pilot to double check the automation's understanding of information. In addition to these features, the communications system will record voice communications so that the pilot can replay a voice message rather than requesting the ground to 'say again,' if the pilot didn't catch the message.

6.4. Notional System

The Notional components of the flight deck are not flight critical, that is, the aircraft can be flown without them. However, they allow the pilot to better prepare for the mission and to handle contingencies. The pilot can use the Notional system to plan the mission, plan contingencies, review plans, rehearse mission elements, explore potential outcomes, and predict future weather and traffic patterns. The key component of the Notional system is the Interactive Trip Planner.

6.4.1. Interactive Trip Planner

The Interactive Trip Planner or ITP provides complemation for the Notional aspect of the mission. The ITP is a portable device (perhaps a tablet PC or PDA) that can be used for intelligent planning of missions. The pilot can develop a flight plan, alternates, plan tasks, play out 'what-if' scenarios and even simulate a flight using the ITP. The ITP can check on legal requirements and insure that the pilot is aware of what requirements need to be met. The ITP can assist the pilot in reviewing or rehearsing tasks. The ITP may even set up the mission by electronically filing a flight plan or detecting that certain equipment is available (e.g., making reservations or requests at ground facilities). The ITP either can be carried on to the aircraft and installed on the instrument panel or it can communicate its information to a mirror ITP permanently installed in the aircraft.

The ITP is extremely memory intensive and dependent. While it will rely on external sources of information, it needs to maintain a great deal of data in order to form a robust description of the situation and the rules and procedures appropriate to that situation. This includes (but not limited to) terrain information, airport information, airport and airspace procedures, communications protocols, regulatory rules and requirements, aircraft information and procedures, and pilot information and limitations.

The ITP will generally communicate with the pilot in a human-like fashion, accepting complex instructions, requesting clarifying information, inferring missing information, and reasoning in an integrated fashion (big picture) using mission goals and sub-goals. The primary function of the ITP is the planner.

6.4.1.1. Planner

The pilot creates a mission plan using the ITP. He inputs or selects the critical criteria of the flight such as the origin, destination, aircraft, and time and date requirements. The planner then constructs a number of legal routes that satisfies those criteria. These routes can vary in terms of cost, duration, complexity/difficulty, or risk. The pilot can select from among these routes. The pilot can then modify the route plan using a number of interface tools (object manipulation, voice, keyboard, multiple choice). In general, the ITP will insure that the pilot can only create a legal route, and will prevent him from making an illegal modification[3]. The ITP will query various information sources to determine current and predicted conditions (e.g., special airport procedures, special use airspace, traffic and weather) and will adjust the plan accordingly.

The ITP will create plans for alternates and will compute the fuel required for the route. It determines compliance with the minimum equipment list (MEL) and the desired configuration list (DCL) for the mission. The ITP will create a plan for the pilot to alert him to changes in the velocity vector or the behavior of the aircraft. This plan will be used by the Actual system to provide guidance and alerting to the pilot and the H system. The pilot may add alerts to the plan based on time, location, or event (e.g., Notify me when fuel quantity is less than …).

6.4.1.2. Simulator

The ITP contains a robust simulator of the aircraft and the geographic and weather environments. This simulator serves two purposes. The first is to validate plans created by the ITP to insure that they are

[3] There may be conditions where the pilot is allowed to make illegal modifications, but these should be rare and the pilot will be prominently and sufficiently alerted.

feasible. The second is to allow the pilot to train, rehearse and review certain aspects of the flight and to explore different options in a benign environment before committing to one in the Actual system.

Out of the aircraft, the pilot could connect inceptors and displays to create a low cost simulator to use for training. It is not uncommon for pilots to test and explore systems and ideas in flight because they have no way of doing so anywhere else. This, of course, may be unpredictable or even dangerous. The simulator in the ITP could provide this benign sandbox for the pilot to explore the options of his aircraft. In addition, the pilot could explore what would happen in the case of certain failures and practice responding to these failures. This would enhance recurrent training, which would reduce the cost of operation of the aircraft.

7. Operational Scenarios

This section is an attempt to 'flesh-out' the components described above. It is important for the reader to remember that any details in this section should not be considered to be design decisions but rather speculations on the part of the authors. A host of research questions will need to be addressed before the final NFD design can be described at this level of detail. The final design may not look or function like this description at all. Indeed, some of the details described below may not be feasible.

7.1. Normal Operations

This scenario describes a nominal trip taken by the pilot. The pilot decides to make a trip from X to Y. He pulls out his ITP and begins a new trip plan. He selects X, Y, the time, date, and the airplane he wants to use. The ITP then performs several operations. It checks the availability and the status of the aircraft. It creates three different safe and valid routes. One route is the shortest time, the second is the lowest cost, and the third is the most comfortable (e.g., extremely risk aversive, avoiding any potential bumpy rides or congestion, easy to fly). The pilot can pick from other route qualifications such as 'scenic' or the pilot can open a previously saved route.

The pilot then enters the route review and modification mode on the ITP and reviews the routes that the ITP has generated and picks one of them. He can then modify the route using direct object manipulation, however he cannot modify the route in such a way as to make it invalid or unsafe or incomplete. If he tries to do so the ITP informs him of the reason he cannot modify it as he wishes and what else he would have to change if he wanted to make that modification. For example, if the pilot tries to add a waypoint on the route that is out of range of the aircraft's currently fueled range, he will not be allowed to do so – however, the ITP will suggest ways to add that waypoint such as adding fuel, using an aircraft with a different range specification, or landing along the way to refuel. The pilot can make quantitative adjustments (using digit wheels, keyboard or voice input) on each quantitative piece of data (e.g., altitude, airspeed).

Once the route is selected and modified, the ITP generates alternates for that route and a pilot task plan. If the ITP has a pilot's log feature, it may compare the regulatory requirements for flying the mission with the capabilities and qualifications of both the aircraft and the pilot. If the pilot has flown the route before and the ITP detects changes from that previous route (e.g., different procedures at the destination airport), the ITP can alert the pilot to those differences.

The pilot can then review the details of the route using the ITP. He can do so in a number of ways. The most basic is simply a plan and profile view that allows the pilot to skip from waypoint to waypoint along the route, with each waypoint displaying the pertinent mission data (e.g., time, altitude, airspeed, fuel).

Another option is to set up the ITP to show the primary flight displays (e.g., perspective, plan, profile) and perform a fast-time simulation of the planned flight. This simulation would be performed according to the plan without pilot input – that is, the simulation would simply be 'playing' the planned flight. Another option might include connecting the ITP to additional displays and inceptors and allowing the pilot to practice flying the route. For any of these options the pilot can select to review only certain portions (e.g., landing).

The ITP is capable of filing the flight plan with the appropriate airspace management authorities and will do so on pilot request.

The pilot then carries the ITP to the aircraft. The ITP presents checklists for preflighting the aircraft. The pilot then installs the ITP in the aircraft and it communicates the intended mission with the rest of the aircraft systems. All aspects of the flight (e.g., schedule, current weather forecasts, tasks) are loaded onto a shared information database (located in the Actual system.) The pilot initiates an engine start and the aircraft emits an engine start signal to warn anyone in the proximity of the starting engine. While starting the engine, the aircraft requests permission to start the mission from the authorities. Once cleared, the Pathway displays (e.g., perspective, plan display, profile displays and any HUDs, canopy displays, or other conformal visual displays) show the cleared guidance path.

- A **Guidance Path** consists of five display elements. They are a tube (visible only outside the tube), centerlines (floor and ceiling if in air, floor only if on ground), guardrails (one on either side of the path), speed rings (where spacing between rings denotes speed), and pace rings (additional cues to provide a natural depiction of the speed – pace rings travel along the path at the guidance speed). All these elements are relative to the inertial path, not the aircraft. Thus, if the aircraft were to be banked at 90 degrees, the guardrails will be on the top and bottom from the pilot's perspective.

- A **tube** is semi-transparent with a shading of either yellow or magenta. A yellow tube is a published route or pathway that is not in the current mission plan. A magenta tube is part of the mission plan (it does not matter whether it is published or not). Tube radii are generally some function of the wingspan of the aircraft (3 or 4 times). Thus the aircraft can fly inside a tube. However, tubes are invisible when inside them in order to avoid unnecessarily tinting the information on the Path display. Thus the pilot can see a tube when he is outside of it as a reference of a path to fly to. However, once inside the tube, the pilot can depend on centerlines and guard rails for directional guidance.

- **Guardrails** are long narrow cylinders that run on either side of the tube (90 degrees from the centerlines). Guardrails serve to provide additional boundary cues for directing the path of the aircraft. In addition, the color of the guardrail is an indicator of the type of path. A magenta guardrail indicates the ITP selected path. Yellow guardrails indicate a published path (e.g., jetway, approach to another runway). Guardrails are visible both inside and outside the tube.

- **Centerlines** are thick lines drawn on the top and bottom of the tube. Centerlines can be green, yellow, or red. A green centerline represents that the aircraft is cleared to follow the path and that it is safe to do so. A red centerline indicates that the aircraft is either not cleared or it is not safe to follow the path. A yellow centerline indicates that the pilot is on a route that does not require a clearance – that is, it is a published or planned path that the pilot can fly at his discretion. Note that in these cases, the pilot (and aircraft) will probably be responsible for self-separation and see-and-avoid. Also note that if the pilot is flying on a published path, that is not a planned mission path (yellow guardrails) and in an airspace that does not require clearances (yellow centerlines) the pilot cannot use the rails and lines as redundant horizon indicators. Centerlines are visible both inside and outside the tube.

- **Speed rings** are only present when there is speed guidance. Speed rings are narrow tori that band around the tubes at regularly spaced intervals. The spacing represents the distance covered in a unit of time (TBD) at that speed. Thus, the faster the speed, the further the space in between the rings. Speed rings are visible both inside and outside the tube.

- **Pace rings**, like speed rings, are only present when there is speed guidance. Additionally Pace rings are not present when a clearance is required and there is none (i.e., the centerline is red). Pace rings are tori similar to speed rings. The distance between Pace rings is based on some fixed length (perhaps related to the length of the aircraft). The Pace rings travel along the tube at the guidance speed. Thus, the pilot can try to 'catch the ring' and keep pace with it as an approximate indication of speed. To avoid clutter, pace rings become invisible when the aircraft is traveling at the proper speed.

The desired speed is indicated both as a bug on the speed display but also as pace rings surrounding the path. When the aircraft appears to be moving at the same speed with these rings, he is at the prescribed velocity. The pilot controls direction and speed using the direction stick and the speed lever. Both are force feedback driven in order to provide two-way communicate between the aircraft and the pilot. While on the ground, the direction stick will only direct lateral movements (i.e., left and right). The pilot moves the speed lever and direction stick to command the aircraft down the desired taxiway towards the runway. The pilot is actually communicating with the 'piloting' portion of the aircraft (hereafter called the H). If the aircraft has not been cleared to move, there will be no green centerline or pace rings and the H will present slight resistance on the speed lever and will issue an objection (aural and/or visual). The pilot may still command the H to move and it will do so, but reluctantly. If the pilot stops issuing commands, the H will move the aircraft to a safe state. For example, if the pilot has commanded the aircraft to move before a clearance has been issued, the H will provide a slight resistance but move. The pilot will have to apply some pressure to keep the command engaged. If the pilot releases pressure, and if the H is in a safe spot on the taxiway, it will slow to a halt. However, if the pilot removes pressure and the aircraft is crossing a clear yet active runway for example, it will continue across the runway until it is safe on the other side. This is the basic behavior of the H.

- The H will move the aircraft at the pilot's command without impedance if the command is for a safe (no threat based on criticality, general probability, and sensed danger) and legal (cleared with all authorities and according to airspace rules) maneuver.

- The H will move the aircraft at the pilot's command with mild resistance on the stick and/or speed lever and with aural and/or visual objections if the command is for a safe but invalid (e.g., not cleared, violation of rules) maneuver.

- The H will move the aircraft at the pilot's command with heavy resistance on direction stick and/or speed lever and with aural and visual warnings if the command is for an unsafe maneuver.

If the aircraft is cleared and the H senses no danger it will obey the pilot's commands to follow the cleared path. The pilot must make all 'gross' or high-level turn commands and speed commands. The H will achieve and maintain the aircraft direction and speed according to those commands and subject to the rules mentioned above. The H will alert the pilot aurally, visually and/or haptically when a planned turn or speed change is approaching. The H will provide a distinct alert when the turn or speed change should be executed. The H will provide a distinct warning when a turn or speed change has been missed. The H will not execute the turn or speed change (except under very special conditions to be discussed later and with very specific consequences).

- The H will alert the pilot when a planned change in the velocity vector of the aircraft is approaching.
- The H will alert the pilot when a planned change in the velocity vector should be executed.
- The H will alert the pilot when a planned change in the velocity vector has been omitted.
- The pilot is responsible for commanding all high-level velocity vector changes.
- The H will not execute a planned change in the velocity vector (except under special circumstances).

The pilot follows the cleared green centerline along the taxiway. If there is a hold point, the H will resist violating it (which means it will slow down and stop if the pilot does nothing at the hold.) The centerline ahead will no longer be marked with green but red instead. When the aircraft is cleared to continue, the centerline ahead will turn green and the pilot can command the H to move forward and the H will move the aircraft with no resistance.

Eventually, the aircraft will approach the active runway for takeoff. When the aircraft may proceed onto the runway (e.g., cleared if the airport is towered), the pilot commands the turns for the aircraft to move into takeoff position.

The pilot then initiates the takeoff behavior, causing the aircraft to take off. The pilot does not need to control the aircraft once the behavior has been initiated.

- **Behaviors** are a complex series of apropos aircraft control adjustments (thrust, lift, drag) and attitude adjustments (pitch, yaw, heading) that are performed by the H in response to a single command given by the pilot. Examples of behaviors are takeoff, land, path interception and following, performance maneuvers (e.g., best climb) and holding (entering and executing a holding pattern). Other potential behaviors are go-around, follow (another aircraft), emergency ditch, emergency force-land or a doglegged delay for meeting a 4D restriction. However, it is important to limit the number of behaviors to a set that is both memorable for the pilot and that is intuitively manageable.

When performing the takeoff behavior the H will accelerate to takeoff speed, monitor for V1, rotate at VR, and climb at V2. The H senses the runway for obstructions or dangers and will avoid them if possible including aborting the takeoff before VR according to rules and procedures. The H will then climb the aircraft to a specific departure point.

There are many potential implementations for the initiation of behaviors. Here are two potential implementations for the takeoff behavior:

7.1.1. Implementation 1

- The pilot advances the speed lever to the maximum position. The maximum position is not up against the 'firewall' or full deflection but rather the maximum ground speed for the aircraft.
- The pilot pulls back on the direction stick full deflection. This does not cause the aircraft to pitch up because it is on the ground. If the aircraft meets requirements (e.g., MEL) and safe for takeoff, this act removes the max ground speed restriction.
- The pilot then pushes the speed lever to its maximum forward deflection while holding the

direction stick full back.

These two full deflection inputs signal the H for a takeoff maneuver. The H signifies that it is performing the takeoff behavior and the pilot can let go of the speed lever and stick.

7.1.2. Implementation 2

- The pilot advances the speed lever to the maximum position. The maximum position is not up against the 'firewall' or full deflection but rather the maximum ground speed for the aircraft.
- The pilot presses a dedicated switch on the direction stick that indicates takeoff.
- If the aircraft is safe and meets requirements for takeoff, these two inputs signal the H for a takeoff maneuver. The H signifies that it is performing the takeoff behavior and the pilot can let go of the speed lever and stick.

The H takes the aircraft off and flies to the departure point that it was assigned. If the airport does not have published procedures the H simply flies to its 'standard' departure point or exiting condition. This point marks the end of the behavior. As the aircraft is approaching this point, the H alerts the pilot that he will have to command the velocity vector from this point. The departure procedure (assigned, published or H-standard) is presented to the pilot as guidance on the Path displays. The pilot is then responsible for making the velocity vector commands. If the pilot does not, the H will warn the pilot that the point has been missed and maintain the velocity vector it was holding at the departure point as long as it is safe to do so. If, for example, this velocity vector would move the aircraft into other traffic, the H will direct the aircraft to a safe vector. It may well be that the safest vector to turn to is indeed the first vector in the departure procedure. However, it is important to note that the H is NOT performing the mission departure procedure. It is performing its own safety maneuver, which in this case is coincident with the departure. However, several things are happening in the aircraft cockpit and in the reasoning logic of the H that are different from what would be happening if the pilot were commanding the aircraft to the mission departure path. The H is providing extremely clear and obtrusive warnings to the pilot in an attempt to have the pilot regain control. In addition, the H may be signaling control authorities of the pilot's lack of input (this is a legal point). The H is also now considering that the pilot may be incapacitated. The H will look for confirming signs (or non-signs) to establish this. These signs are a design and research question but they might include detecting if the pilot makes the expected appropriate control inputs, detecting if the pilot makes any control inputs at all, having the pilot silence the warning using a combination of inputs (e.g., a keypad entry) or some combination of these[4].

The purpose of having the pilot make the inputs rather than simply having the H fly is to engage the pilot in a meaningful way without overwhelming him or requiring significant aviation skills.

Normally, the Path displays will be presenting guidance in the form of magenta guidance paths. For the remainder of the flight, the H will alert the pilot to upcoming turns and/or speed changes and the pilot will command those changes using the direction stick and speed lever. The pilot commands the velocity vector by using the direction stick to point a command icon (the H-coa) on the path displays 'into' the tube of the next guidance path. Once in that tube, the H will maintain the velocity vector. The pilot and H continue to work together in this manner throughout the rest of the flight, if there are no changes to the path created by the ITP. If the pilot wishes to move to another vector or form of guidance, the pilot can simply point the H-coa at the guidance and the H will highlight it, in a sense asking the pilot if this is

[4] If the pilot is in a high workload tactical situation, it is likely that he will have a command input of some kind and that should silence the alert. If the pilot is entering a long leg and would not normally have to enter a command to silence the warning, he could then use the keypad since he has time. If this scheme were used, the pilot might find it easier to enter in a command input that was off the intended path (thus silencing the alarm) and then put the aircraft back on the path. However, a command off the path will signal a different alert and perhaps make a note in the log.

what he wants to do, the pilot can respond yes or not. If yes, then the H will proceed on the most efficient way to intercept the guidance. For example, if the pilot wants to fly to a certain lat/long (i.e., a waypole), he simply moves the direction stick until the H-coa is on the waypole. As the H-coa is close to the waypole, it will have a slight magnetic tug in the direction of the waypole as further indication that there is a valid target. The H will highlight this pole. The pilot can signal the H (perhaps through some discrete input on the direction stick) that this is the new target. When the H accepts the waypole as a target, it will then allow the pilot to make lateral changes and speed changes to lock on to a particular altitude on the pole and a particular time of arrival at that pole. Speed is displayed not only as airspeed but also as time to intercept the new target.

On approach to the destination airport, the pilot will direct the aircraft to an arrival point within sight of the runway and at minimum decision altitude. When the H-coa highlights this point, the pilot will initiate a landing behavior. The H will then perform the landing (including flare and roll out). The pilot will then command the aircraft to the hanger, tie down area, or service area in the same manner used to taxi out at the beginning of the flight.

Depending on the airspace management system and the weather, there is a chance that the pilot will have to deviate from the original plan provided by the ITP. If the change is to occur while on the current velocity vector and before the next commanded direction or speed change, the pilot can execute the change simply using the stick and power lever. If the change will take place beyond the next scheduled change and if the pilot has time, he can make that change in the trip using the ITP and this will be communicated to the aircraft plan. He can easily just wait for the aircraft to come to the changed vector and implement the change using the stick and lever. However, he will not have the reminder cueing and could potentially miss the change.

There are several, potentially different goals that the pilot can have for deviating from the planned path. He can leave the planned path to join another published path. He can leave the path to fly to a new heading based on ATC commands. He can fly direct to a particular waypoint. He can fly to a new altitude. Another, more subtle deviation from the path is to change speed.

To leave the current path to join another published path, the pilot must exit the tube. The H offers a slight resistance in the direction stick as if bumping up over a curve. The pilot can then point the velocity vector of his aircraft at the new tube path that he wants to join. When the H-coa crosses the intersection of the current velocity vector and the tube, it highlights the tube. If the pilot accepts the interception, the H plots a course for making a smooth turn into the new tube. The H will then treat this as the next turn in the guidance and will offer alerts for approaching the tube and for executing the turn onto the tube and if the turn is not executed. If the pilot does not turn onto the new tube path but instead crosses over it, he will feel the H bump the direction stick as if riding over railroad tracks. It the pilot does turn the vector onto the tube path; the H will produce a slight bump on entering the tube (as if dropping down off a curb) and will capture and hold the path. If there is speed guidance attached to this path, the H will offer a small detent in the speed lever for maintaining that speed. Since this new path is not a mission path, the H does not know where the pilot wants to turn, thus at every intersection with another guidance path, the H will highlight the possible intersections when the H-coa covers it and is within a certain distance.

If the pilot wishes to turn onto a new heading, he can simply direct the velocity vector onto the desired heading using the heading rose as guidance. Normally the heading target is displayed as a waypole fixed at the desired heading and some fixed distance from the aircraft on the path displays in order to aid the pilot in pointing at it. Thus for heading guidance, the aircraft can be pointed at the waypole but it will never reach it because it is constantly moving with the aircraft. In this case, there are no tubes. The H may recognize that it is heading towards the target and provide a slight 'locking on' feature that pulls the H and thus the haptic feedback, towards the target. The H will simply drive at the commanded velocity vector. If the pilot turns there is no resistance from the H. There are other salient cues that indicate that the pilot is not on a predetermined path.

If the pilot wants to fly to a particular point in space, he simply aims the velocity vector at that point. Normally the target is presented on the Path displays in order to aid the pilot in pointing the H-coa at it. Like the heading change, there are no tubes. However, the H may recognize that it is heading towards the target (if it knows about the target) and provide a slight 'locking on' feature that pulls the H and thus the haptic feedback, towards the target. In other words, as the pilot moves the H-coa icon close to the target, the stick and vector will have a slight 'gravitational' pull towards the target. There are three types of inertial point targets that the pilot could aim at. The first, a waypole, is not technically a point, but represents a latitude/longitude. It is represented as a pole sticking out of the earth at that lat/long. A waypoint is simply a three dimensional point in space. A Crosspoint is a waypoint with a time restriction on it.

If the velocity vector is directed at a waypoint or a waypole, the path display will present the time that the aircraft will arrive at that point. The pilot can vary speed accordingly using the speed lever. The pilot also has a speed indicator on the path display for making speed adjustments without consideration of any waypoints. This is method for commanding the velocity vector is called *Point to Program*.

- *Point to Program* is the use of force feedback, haptic inceptors to command the H (program the autopilot) to achieve a certain velocity vector. The Point to Program concept not only depends on the inceptors but also on the display providing the information needed to make domain specific inputs (e.g., cross waypoint X at time Y).

- A *Wayplane* is a reference of an altitude level. It has no latitude/longitude parameter. It is primarily displayed as a line in the profile view of the path display and it is not displayed in the plan view of the path display. A highlight/selected Wayplane may be displayed as a semi-transparent plan on the perspective view. The Wayplane acts as a path change guidance cue, the H will alert the pilot of the need to level off in the same manner as if the aircraft were coming up on any guidance change.

- A *Waypole* is an inertial reference of latitude/longitude position. It has no altitude parameter. It is displayed as a pole projecting from the ground into infinity. Additionally, it could be presented as a 'haptic' magnet for the direction stick that lets the pilot know that the pole is an object that the H recognizes. The Waypole acts as a path guidance cue, the H will alert the pilot when the aircraft is approaching the Waypole in the same manner as if the aircraft were coming up on any guidance change.

- A *Waypoint* is an inertial reference to a latitude/longitude/altitude position. It is displayed as a regular geometric shape (e.g., sphere, star, cube, cross) on the display. Additionally, it could be presented as a 'haptic' magnet for the direction stick that lets the pilot know that the point is an object that the H recognizes. The Waypoint acts as a path guidance cue, the H will alert the pilot when the aircraft is approaching the Waypole in the same manner as if the aircraft were coming up on any guidance change.

- A *Crosspoint* is an inertial reference to a latitude/longitude/altitude position at a particular time. It is displayed as a regular geometric shape (e.g., sphere, star, cube, cross) that is different from the Waypoint shape on the display. Additionally, it could be presented as a 'haptic' magnet for the direction stick and speed lever that lets the pilot know that the point is an object that the H recognizes. The Waypoint acts as a path guidance cue, the H will alert the pilot when the aircraft is approaching the Waypole in the same manner as if the aircraft were coming up on any guidance change.

The ITP has transmitted its guidance information to the aircraft to be presented on the Path displays. In general, the H does not recognize any of this guidance beyond the next velocity vector change. More specifically, the H recognizes the current velocity vector that the pilot has captured, its termination point, and the new velocity vector that the guidance is presenting. The reason for having the H know about the next velocity vector is so that it can make cue the pilot to make an efficient turn. It is up to the pilot to translate the guidance into an H command. The purpose of having the pilot in this information flow chain is to keep the pilot involved and engaged in what the aircraft is doing and to allow the pilot to intervene if necessary. Thus the pilot is a critical part of this chain from guidance to activation.

7.2. Sample Weather Scenarios

7.2.1. Scenario Title: Wake turbulence from Large Aircraft on Runway

The NFD aircraft is at the end of the taxiway having just been cleared to move onto and hold at the end of the runway. A large aircraft has just taken off. Through ADS-B-like information, the NFD aircraft knows the type of aircraft preceding it in the takeoff queue and the time the takeoff roll for the heavy began. Also available are wind speed and direction at ground level. As the NFD aircraft awaits takeoff clearance, the H system continuously evaluates the likelihood that the wake turbulence from the preceding aircraft is still a hazard and displays to the pilot a suggested hold time. The pilot has received clearance to move on to the runway. The H system informs the pilot, via a display, of the potential hazard from the wake turbulence and the estimated duration of the hazard. If the pilot tries to release the brakes while H system estimates a hazard, the H system resists brake release and gives an auditory warning to the pilot. The pilot can override the H system at any time by some prescribed action. The pilot should now be aware of the situation.

7.2.2. Scenario Title: Icing in terminal area

Aircraft is 10 minutes out from initial approach fix for a RNP approach into a 3000’ runway. It is descending from 5000’ to 3000’ by the IAF. Airspeed is cruise descent, 200kts. The H is leading the pilot through an approach and landing briefing.

The aircraft is descending through a broken cloud layer; the outside air temperature is 23 degrees. Airport elevation is 0’ MSL and its reported conditions are an 800’ ceiling, 1 mile visibility, light and variable winds and an air temperature of 40 degrees. Another slower aircraft is 9 minutes out from the opposite IAF (standard T approaches). From weather datalink and real time sensing, the aircraft is aware of potential light icing and current airport conditions.

No PIREPS of icing have been reported near the airport. The real-time icing sensor has just started to detect light ice accumulation. The system responds to the icing detection by—

- Issuing a caution to the pilot (haptic and visual signals),
- Increasing the approach speed by 15 knots above nominal,
- Restricting the low slow end of the speed envelope and use of flaps, and

- Broadcasting an airplane generated “PIREP” for icing.

The Actual system cautions that landing on 3000’ runway with icing restricted flight envelope does not provide normal safety margin, but predicts that the airplane is likely to reach freezing level at 2000’ and be ice free by landing.

Airplane communicates the situation to the leading traffic and requests that it expedite its approach or delay—confirmation is received that traffic can expedite allowing approach to be flown at higher than normal speed while avoiding potential separation conflict.

The icing sensor continues to measure rate of ice accumulation. The aircraft estimates performance effects of ice accumulation and likely margins. If performance appears nominal and icing sensor detects no icing, the Actual system requests that pilot make qualitative inspection for ice and report status. If pilot also reports no ice, icing restrictions are removed. The Notional system updates the diversion plan as needed to account for current situation.

The aircraft reaches freezing level at 2100’ and recommends continued descent. A data link message is received from the preceding aircraft that it has landed and cleared the active runway. The airplane breaks out of the clouds at 900’ and the pilot signals to the aircraft that he has visual contact with the runway and intends to continue the approach to a landing. At 600’, the airplane uses cues to ask pilot if she confirms that the airframe is clear of ice. On receiving a clear signal from the pilot, the airplane reduces the approach speed only as needed to obtain nominal landing distance margins on the 3000’ runway. Just prior to 200’, both the airplane and pilot confirm that all is well for landing and the airplane transitions to landing behavior when appropriate.

The airplane relaxes ice restriction only as needed to permit safe landing on a 3000’ strip. Both the airplane and the pilot confirm that all is well for landing and the airplane transitions to landing behavior as appropriate.

7.2.3. Scenario Title: Weather change in Notional realm

The aircraft is at cruise on a long flight. The route that the pilot has selected is based on comfort. The pilot is watching a movie. The pilot is engaged in the movie. A turn is approaching in 10 minutes. A storm cell is moving faster than predicted and will cross the flight plan, which will lead to strong turbulence. This crossing is about 45 minutes away. The aircraft has the current plan and pilot preferences. The aircraft does not know that the pilot is watching a movie. The aircraft calculates a decision point at which a decision must be made in order to give the storm cell a wide berth. The pilot has made the plan therefore a portion of that should reside in the pilot’s memory. The pilot knows the last turn that he made. The H will signal that a turn is approaching (exact time and/or distance TBD). As the aircraft comes upon the turn, it will freeze or lock out the Notional system from the pilot until the turn is made. It will then allow the Notional system to be activated. The Notional system will alert the pilot that there is a change in the weather. It will inform the pilot how this violates the current plan (primarily the preferences). It will give the pilot two options – 1) to go around the cell and 2) to reduce the comfort constraint. If the aircraft approaches the decision point, the attention-getting nature of the Notional system will rise up a notch or two. If the pilot does nothing, the last option is automatically selected. If the Notional system is interrupted by the Actual system, it stores the last inputs of the pilot. When the Notional system is reactivated. It has the option to ‘play through’ the last steps that the pilot took so as to refresh the pilot regarding where he was and what he was doing. The pilot can continue on from there.

If the Notional system sounds and the pilot ignores it (either consciously or unconsciously), the Notional system signals again. The pilot pauses the movie. He then directs his attention to the Notional system. He sees the problem and two alternatives that have been suggested by the Notional system. He does not like either one. He decides to try and go behind the cell and experience some turbulence but not as severe. He starts moving the route when the Actual turn signal calls his attention. He ignores it because he thinks he can finish the route changes in time. He tries to make the change, however the Notional system does not allow him to because it is illegal. The Notional system informs him about the illegality and offers another similar solution. While the pilot is reviewing it the Actual turn alert sounds and the Notional display fades, announces that an Actual interaction is required, and does not take any more commands. The pilot turns his attention back to the Actual system and makes the turn. After the turn is made, he returns to the Notional system, which replays his past moves and displays (including his attempt to do something illegal and the explanation). The pilot recalls the situation and the mind set and completes his inspection of the route. He accepts the changes and goes back to watching his movie. The rest of the flight continues normally.

7.3. Sample Traffic Scenarios

7.3.1. Scenario Title: Closure of destination

The pilot and airplane have just started the approach, following a larger commercial airplane into a very busy airport. The airplane is under control - all systems working, fuel state is on plan and everything is progressing normally. The pilot is alert and in control. The weather is clear but a thunderstorm cell is rapidly approaching from the West. The alternate airport is now behind the aircraft to the south of the final destination. The airplane preceding the pilot’s aircraft has a mechanical failure and is stranded on the only active runway at the airport.

ATC broadcasts that the airport is closed and the pilot and aircraft execute a missed approach. The H immediately upon identifying the need to perform a missed approach begins signaling the pilot through the stick, enhancing the image on the windscreen, and generating an audible alert. The enhanced view of the flight path may change to a different color or begin flashing. The normal behavior is for the H to follow the missed approach if the pilot does not indicate their desire to land. The situation is not critical yet so the H waits a short time for the pilot to evaluate the situation and get in the loop. The pilot should initiate the missed approach when directed by ATC. However, if the H senses the pilot is not responding or not executing the ATC requested procedure it may begin to follow the missed approach procedure. The Notional system has been listening to the ATC situation and became aware of the change in plans when the airplane was leveled off to fly the missed approach. It begins by getting an updated weather picture. The Notional system verifies that returning to the planned alternate is not a good idea because of the weather cell that moved in behind the airplane. It retrieves information about the alternates in the vicinity of destination and begins building and checking routes. Since fuel is low and many airplanes in the vicinity will be angling for the larger fields the Notional system determines a smaller field would be better. There is a small unattended airport north and slightly west of the destination that would allow the airplane to land safely. There is no ground transportation available however so the pilot would have to wait for a taxi to come out and pick him up. This alternate is marked as a possible. Other alternates are marked and the information is presented to the pilot. After the pilot selects the one he wants, the Notional system sends information off to ATC and the selected airport advising everyone of the pilot’s intentions to land at the newly selected airport. The Notional system begins feeding the flight legs to the H for guidance, once ATC has cleared them to proceed.

7.3.2. Scenario Title: Runway change at destination

It is night and rainy, the airport is in the middle of the city in a plain terrain with some high-rise buildings nearby. The flight was smooth so far and the pilot has just started to plan for approach when the aircraft receives alerts from the ATC that the scheduled runway cannot be used. ATC requests the aircraft to land on another runway. There is not enough time to enter the information into the Notional system. And there is no need. The approach to the alternate runway is in the H guidance system (as are all approaches to all the runways). This approach is presented on the guidance display and the pilot simply turns off from his course and turns onto the new approach. Once on the new approach, the H signals that it can follow this approach and the pilot executes the appropriate landing behavior when it is time. The new approach continues as normal.

7.4. Sample Aircraft Non/Rare-Normal Scenarios

7.4.1. Scenario Title: Engine out in flight – twin-engine aircraft

The aircraft is at cruise altitude. When the Actual system senses an engine failure, it immediately provides status information to the pilot. It then offers the guidance to the current abort alternate. This path is computed using the single engine capabilities of the aircraft and considers best runway geometry based on aircraft location, capability and wind strength and direction.

The path is displayed on the Actual plan view display as well as the guidance display. The pilot can then follow that plan if he so chooses. To follow the plan, the pilot must turn the aircraft from its current course onto the alternate path. The pilot can also select other alternates that are displayed on the Actual plan display (only a limited set of viable options are displayed. Logic for limiting the set is the subject for further research) If the pilot selects another alternative, the H computes the best path to that airport.

The Actual system informs the Notional system of the need to abort and the reason for doing so (i.e., engine failure). The Notional system determines if there are sufficient maintenance facilities. If so, it then goes on to determine alternate ways to complete the mission (car, other aircraft). If there are not appropriate facilities the Notional system locates appropriate airports that are within a reasonable (given engine loss and fuel status) range of the aircraft. If one exists, it informs the pilot of a better available alternate choice. The Notional system explains why this choice was presented. The pilot can add this new alternate to the current guidance and follow the guidance to that airport.

Once the aircraft is safely on the ground, maintenance will be datalinked information concerning the engine failure. The H will compensate for missing thrust source and allow the pilot to taxi back to the hanger.

7.4.2. Scenario Title: Engine out in flight – single-engine aircraft

The aircraft is at cruise altitude. When the Actual system senses an engine failure, it immediately provides status information to the pilot. It then develops a plan for landing/ditching at the most suitable site given the aircraft’s glide characteristics and whatever information is in the database (e.g., extensive terrain maps). This path is computed using the control characteristics of the aircraft and considers best landing geometry based on aircraft capability and wind strength and direction. The pilot must then consult the plan and either accept or reject it.

The path is displayed on the Actual plan view display as well as the guidance display. The pilot should then follow that plan if he so chooses. To follow the plan, the pilot must turn the aircraft from its current course onto the alternate path. The pilot can also select other alternates that are displayed on the Actual plan display (only a limited set of viable options are displayed. Logic for limiting the set is TBD. If the pilot selects another alternative, the H computes the best path to that landing site.

The Actual system broadcasts the declaration of emergency, cause of emergency, intentions, and the location of the aircraft. Once the aircraft is safely on the ground, rescue, maintenance, and ground transportation will be datalinked information concerning the engine failure.

7.4.3. Scenario Title: Notional System failure in flight

The Actual and Notional System each contain a mirrored database that contains terrain, airport, weather, and airspace information. The plan that is created by the Notional system (including alternates) is also contained in this shared database.

If the Notional system fails, the pilot is notified by the Actual system. The guidance on the Actual system remains the same since it is the same as the Notional system was providing before it failed.

The pilot is reminded that the Notional System will not be available to check for situational changes in the predicted future. The human will have to assume the back-up role for the Notional system. The Actual system modifies its behavior to complement the human in this new task in the following ways. 1) The pilot can use the Actual plan view display to 'scroll' ahead in the route. In other words, the Actual plan view display is no longer locked to the aircraft. 2) The Actual system will provide periodic (and appropriate) reminders to the pilot to check current conditions and compare with predicted conditions. 3) The Actual system (after sufficient and salient notification to the pilot) will follow the guidance even if the pilot has not command the aircraft to do so. 4) All standard/published airways will be visible in the Actual system to make it easier for the pilot to locate them and fly to them. (This encourages the pilot to either fly the planned route or to fly on published paths.)

7.4.4. Scenario Title: H-mode system haptic cueing failure in flight

The pilot has continuous 'recurrent' training on flying the aircraft because of the cooperative interaction between the H and the pilot using haptic feedback normally available through the stick. The pilot will develop expectations on what the H-would do based on experience. Should the cueing of the H fail; the pilot should have a mental model of what the H would have cued him because this is what has been encouraged during normal operations. Thus, the pilot should be able to make intelligent responses based on conditioned, skill-based behavior. The Actual system should also be forgiving of pilot errors in stick commands.

7.5. Sample Human Non/Rare-Normal Scenarios

7.5.1. Scenario Title: Pilot incapacitation

The Actual system displays guidance to the pilot and signals the pilot when to perform the maneuvers. If the pilot fails to perform, the Actual system will make concerted efforts to engage the pilot's attention. If the pilot is still not responding, the Actual system will announce a potentially incapacitated pilot and fly to the nearest airport (note that this is not necessarily the alternate that pilot may have selected). It will not take facility or transportation considerations into account. This would simply be the fastest way down. The H will perform the landing on its own, unless the pilot tries to intervene. If the pilot intervenes, the H will return to its normal operations.

8. Summary and Discussion

8.1. NFD Summary

The goal of this program has been to make operating an aircraft easier and more intuitive while also making it safer. Either goal is ambitious, but we believe that the approach we have taken and the concepts that we have designed will not only achieve both of these goals but will do them elegantly. Perhaps the central tenet of this approach has been to consider the entire flight experience in the design process rather than just an isolated element. The NFD concept accounts for performing the flight, planning for the flight, dealing with unexpected occurrences, rehearsing for the flight, and reviewing the flight. The application of design metaphors to each of these functions has enabled us to develop what we consider to be a consistent, comprehensive, and cohesive design that is expandable as to accommodate new technologies as they mature.

The design strives to engage the human in the operation of the vehicle in such a way that the human is not overwhelmed with either mental or physical workload yet feels meaningfully involved in the flight. The design assumes that one of the human's more important roles in the flight deck is looking at the big picture and dealing with unexpected or unanticipated occurrences. Therefore, the human is called upon to make high-level changes in the flight in order to keep him in the loop, while the automation handles the inner loop control and monitoring (which would tax the human if it were assigned to him).

The automation in the NFD is used to collect and store knowledge of the domain (e.g., simulation of the vehicle, airspace rules and regulations, weather information), to monitor the mission, the environment, the vehicle and the pilot, to alert the pilot to tasks and conditions, and to perform precision, deterministic, and repetitive tasks. The vehicle possesses horse-like intelligence but not human-like intelligence. This allows the pilot to have a natural interaction with the vehicle without expecting it to 'think' for the human.

8.2. Human Centered vs. Technology Centered

Perhaps the most common criticism of this design approach is that it does not utilize the full potential of automation. Many feel that a more fully automated vehicle would be more satisfactory approach. Rather than having the human to be involved with the control of the vehicle at all, the human could enter a mission goal and the machine would perform the goal – much like a chauffer. They argue that current airline transports have flight management systems that allow the pilot to program the route and then watch the airplane fly the route. The problem with these approaches is that they do not account for the unexpected or unanticipated. And yet aircraft carrying humans have to deal with the two most unpredictable phenomena – human beings (involved in the design, manufacture, and operation) and weather. Massive amounts of research and computational modeling and computing power have been pressed into the service of predicting weather and yet, while good, they are nowhere near 90% correct. This is not acceptable. The human complemented by the machine can perform much more effectively and can implement common sense solutions to problems that machines cannot. However, in order to do so, they must be aware of what is going on. While it is possible for them to be passively aware, this becomes more difficult as reliability increases – humans become bored and complacent. Involving them in meaningful ways without overloading them should keep them aware of the situation so that if an unexpected event occurs they will not be caught unawares.

In short, we believe that the Naturalistic Flight Deck concept approaches an optimal use of technology in human-machine systems. Of course, much research and development remains in order to evaluate this claim. However, the combined benefits of ease of use and increased safety make it a worthwhile task.

9. References

AOPA (2003). *2003 Nall Report: Accident Trends and Factors for 2002*. Frederick, MD. AOPA Air Safety Foundation

Baddeley, A. (1998). Human Memory: Theory and Practice (revised ed.). Boston: Allyn and Bacon.

Bainbridge, L. (1983). "Ironies of Automation." London England, University College London, Department of Psychology

Benenson, T. (2003, June). "Cheap Jets are Here Now." Flying Magazine.

Bergeron, H. P. (1980). *Analysis of General Aviation Single Pilot IFR Incident Data Obtained from the NASA Aviation Safety Reporting System*. (NASA TM-80206). Hampton VA: NASA Langley Research Center

Best, J. R. (1999). What is attention? In Cognitive psychology (5 ed., pp. 45-60). Boston: Brooks Cole.

Billings, C. E. (1997). Aviation automation: The Search for a Human-Centered Approach. Mahwah, NJ: Lawrence Erlbaum Associates.

Boeing anonymous (2004). *Statistical Summary of Commercial Jet Airplane Accidents, Worldwide Operations 1959-2003*. Boeing Commercial Airplanes, Seattle WA.

Bureau of Transportation Statistics. (2007). National Transportation Statistics. Retrieved 10/5/2007, 2007, from http://www.bts.gov/publications/national_transportation_statistics/pdf/entire.pdf

Collins, R. L. (1993). *Flying IFR*, 3rd Edition. Charlottesville VA, Thomasson-Grant, Inc.

Collins, R. L. (2003, December). "Alone at the Top". Flying Magazine.

Duerksen, N. (2003). "Advanced Flight Controls and Pilot Displays for General Aviation", AIAA 2003-2647. Paper presented at the 2003 AIAA/ICAS International Air and Space Symposium and Exposition, Dayton Ohio.

Dollyhigh, S. M. (2002). Analysis of Small Aircraft as a Transportation System. (Contractor Report No. NASA/CR-2002-211927). Hampton, VA: NASA Langley Research Center.

Downen, T. D., Hansman R. J. Jr. (2002). Analysis of Barriers to the Utility of General Aviation Based on a User Survey and Mode Choice Model. (Report No. ICAT-2002-01). Cambridge MA: MIT International Center for Air Transportation.

Flemisch, F. O., Adams, C. A., Conway, S. R., Goodrich, K. H., Palmer, M. T., & Schutte, P. C. (2003). The H-metaphor as a guideline for vehicle automation and interaction. (Technical Memorandum No. NASA/TM—2003-212672). Hampton, VA: NASA Langley Research Center.

Forsyth, D. L., Shaughnessay, J. D. (1978). Single Pilot IFR Operating Problems Determined from Accident DATA Analysis. (NASA TM-78773). Hampton, VA: NASA Langley Research Center

Guohua, L., & Baker, S. P. (2007). Crash Risk in General Aviation Journal of American Medical Association, 297(14), 1596 - 1598.

Hansman, R. J. (2004). “Overview of Recent Trends in the Airline Industry”. Cambridge MA: MIT International Center for Air Transportation.

Klein, G. A., Orasanu, J., Calderwood, R., & Zsambok, C. E. (Eds.). (1993). Decision making in action: Models and methods. Norwood, NJ: Ablex Publishing Company.

Miller, C., & Hannen, M. (1999). The rotorcraft pilot's associate: Design and evaluation of an intelligent interface for a cockpit information manager. Knowledge Based Systems, 12, 443-456.

Mozdzanowska, A. Hansman, R. J. (2004). Evaluation of Regional Jet Operating Patterns in the Continental United States (ICAT Report No. 2004-1). Cambridge MA: MIT International Center for Air Transportation

Norman, D. A. (1990). The problem with over automation: Inappropriate feedback and interaction, not over-automation. In D. E. Broadbent, J. Reason & A. D. Baddeley (Eds.), Human factors in hazardous situations. Oxford: Clarendon Press.

Norman, D. A., & Draper, S. W. (Eds.). (1986). User centered system design: New perspectives on human-computer interaction. Hillsdale, NJ: Lawrence Erlbaum Associates.

NTSB (2004). *Annual Review of Aircraft Accident Data: U.S. General Aviation, Calendar Year 2000*. Washington, DC: National Transportation Safety Board

NTSB (2004). *Annual Review of Aircraft Accident Data: U.S. Air Carrier Operations, Calendar Year 2000*. Washington, DC: National Transportation Safety Board

Onken, R. (1999, October 17 - 19, 1999). The cognitive cockpit assistant systems CASSY/CAMA. Paper presented at the World Aviation Conference, San Francisco, CA.

Parasuraman, R., Mouloua, M., Molloy, R., & Hilburn, B. (1996). Monitoring of automated systems. In R. Parasuraman & M. Mouloua (Eds.), Automation and human performance: Theory and applications (pp. 91-116). Mahwah, NJ: Lawrence Erlbaum Associates.

Palmer, M. T., Rogers, W. H., Press, H. N., Latorella, K. A., and Abbott, T. S., (1994). A Crew-Centered Flight Deck Design Philosophy for High-Speed Civil Transport (HSCT) Aircraft, (Technical Memorandum No. NASA/TM—109171). Hampton, VA: NASA Langley Research Center.

Pope, A. T., Bogart, E. H., and Bartolome, D. S. (1995). Biocybernetic System Validates Index of Operator Engagement in Automated Task. Biological Psychology, 40, 187-195.

Pope, A. T.; and Bogart, E. H. (1993). Identification of Hazardous Awareness States in Monitoring Environments. SAE Technical Paper No. 921136, SAE 1992 Transactions: Journal of Aerospace, Section 1 - Volume 101, pp. 449-457.

Reeves, B., & Nass, C. (2003). The media equation: How people treat computers, television, and new media like real people and places. Stanford, CA: Center for the Study of Language and Information.

Riley, V., DeMers, B., Misiak, C., & Schmalz, B. (1998). The cockpit control language: A pilot-centered avionics interface. Paper presented at the Human Computer Interaction - Aeronautics, Montreal, Québec.

Schutte, P. C. (1999). Complemation: An alternative to automation. Journal of Information Technology Impact, 1(3), 113-118.

Schutte, P. C. (2000). Distance: A metric for flight deck design and function allocation. Paper presented at the 44th Annual Meeting of the Human Factors and Ergonomics Society, San Diego, CA.

Schutte, P.C. (1997). Wings: A New Paradigm in Human-Centered Design. Paper presented at the 9th International Symposium on Aviation Psychology, Columbus, Ohio.

Schutte, P. C. & Trujillo, A. C. (1996), Flight Crew Task Management in Non-Normal Situations, Proceedings of the Human Factors and Ergonomics Society 40th Annual Meeting, Philadelphia, PA.

Smith, D. M., & Broadwell, M. M. (1986). The pilot's associate - an overview. Paper presented at the 8th Annual Workshop on Expert Systems and Their Applications, Avignon, France.

TAA Safety Study Team, Fiduccia, P., Wright, R. co-chairs (2003). General Aviation Technically Advanced Aircraft: FAA-Industry Safety Study. (http://www.faa.gov/avr/afs/fits/documents/TAA%20Final%20Report.pdf)

Trujillo, A. C. (2002). Vertex movement for mission status graphics: a polar-star display, (Technical Memorandum No. NASA/TM—2002-211414). Hampton, VA: NASA Langley Research Center.

Wiener, E. L. (1988). Cockpit automation. In E. L. Wiener & D. C. Nagel (Eds.), Human factors in aviation (pp. 433-461). San Diego, CA: Academic Press.

Wiegmann, D.A., Shappell S. A. (2001). *A Human Error Analysis of Commercial Aviation Accidents Using the Human Factors Analysis and Classification System (HFACS).* Washington D. C.: Office of Aviation Medicine, Federal Aviation Administration.

Wiegmann, D.A., Shappell S. A., et al (2005). *A Human Error Analysis of General Aviation Accidents: A Comprehensive, Fine-Grained Analysis Using HFACS.* Atlantic City International Airport, NJ, Federal Aviation Administration.

Woods, D. D. (1996). Decomposing automation: Apparent simplicity, real complexity. In R. Parasuraman & M. Mouloua (Eds.), Automation and human performance: Theory and applications (pp. 3-17). Mahwah, NJ: Lawrence Erlbaum Associates.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)*
01- 12 - 2007

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
The Naturalistic Flight Deck System: An Integrated System Concept for Improved Single-Pilot Operations

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Schutte, Paul C.; Goodrich, Kenneth H.; Cox, David E.; Jackson, E. Bruce; Palmer, Michael T.; Pope, Alan T.; Schlecht, Robin W.; Tedjojuwono, Ken K.; Trujillo, Anna C.; Williams, Ralph A.; Kinney, J. Bryan.; and Barry, John S., Jr.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
609866.02.07.07

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, VA 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER
L-19285

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)
NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NASA/TM-2007-21500

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 06
Availability: NASA CASI (301) 621-0390

13. SUPPLEMENTARY NOTES
An electronic version can be found at http://ntrs.nasa.gov

14. ABSTRACT
This paper reviews current and emerging operational experiences, technologies, and human-machine interaction theories to develop an integrated flight system concept designed to increase the safety, reliability, and performance of single-pilot operations in an increasingly accommodating but stringent national airspace system. This concept, know as the Naturalistic Flight Deck (NFD), uses a form of human-centered automation known as complementary-automation (or complemation) to structure the relationship between the human operator and the aircraft as independent, collaborative agents having complimentary capabilities. The human provides commonsense knowledge, general intelligence, and creative thinking, while the machine contributes specialized intelligence and control, extreme vigilance, resistance to fatigue, and encyclopedic memory. To support the development of the NFD, an initial Concept of Operations has been created and selected normal and non-normal scenarios are presented in this document.

15. SUBJECT TERMS
Artificial Intelligence; Avionics; Complemation; Flight Deck; H-mode; Human Factors; Metaphor; Strategic; Tactical

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			STI Help Desk (email: help@sti.nasa.gov)
					19b. TELEPHONE NUMBER ***(Include area code)***
U	U	U	UU	63	(301) 621-0390