OPEN PLATFORM FOR LIMIT DISPLAY, CAREFREE MANEUVER, AND LIMIT PROTECTION

Geoffrey J. Jeram
Graduate Research Assistant
geoffrey_jeram@ae.gatech.edu

Dr. J.V.R.Prasad
Professor
jvr.prasad@aerospace.gatech.edu

School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia

ABSTRACT

This Open Platform for Limit Protection guides the open design of maneuver limit protection systems in general, and for manned, rotorcraft, aerospace applications in particular. The platform uses three stages of limit protection modules: limit cue creation, limit cue arbitration, and control path interface. A common set of limit cue modules provides commands that can include constraints, alerts, transfer functions, and friction. An arbitration module selects the "best" limit protection cues and distributes them to the most appropriate control path interface. This platform adopts a holistic approach to limit protection whereby it considers all potential interface points, including the pilot's visual, aural, and tactile displays; and automatic command restraint shaping for autonomous limit protection. For each functional module, this thesis guides the control system designer through the design choices and information interfaces among the modules. Limit cue module design choices include type of prediction, prediction mechanism, method of critical control calculation, and type of limit cue. Special consideration is given to the nature of the limit, particularly the level of knowledge about it, and the ramifications for limit protection design, especially with respect to intelligent control methods such as fuzzy inference systems and neural networks. The Open Platform for Limit Protection reduces the effort required for initial limit protection design by defining a practical structure that still allows considerable design freedom. The platform reduces lifecycle effort through its open engineering systems approach of decoupled, modular design and standardized information interfaces.

NOTATION

ζ = 2nd order system damping coefficient
ω = 2nd order system natural frequency
μ = Force or position command switch
λ = Lagrange coefficient for Limit Margin. Positive values indicate "within limits".
Δu_{crit} = Control margin
Δy = Limit margin
f , g , h= Vector functions
F = Force applied to Sidestick
K = Scaling factor
N = Limit Identifier
t = time, (Δt = time or sample interval)
u = Input signal for a control sub-system
x = Aircraft State Vector
y = Aircraft Limit Vector
y_p = Predicted Limit Vector

Superscripts and Subscripts

λ = Lagrange multiplier coefficient
δ = Inceptor physical displacement
δu = position to control command scaling
+ = Positive or Upper, as in u^{+}_{crit}
- = Negative or Lower, as in u^{-}_{crit}
ANN = Adaptive Neural Network
C = Aircraft characteristic, as in Y_C (s)
crit = Critical
F = Force or Force-Feel, as in $u_{F.long}$
f = Fast, as in fast states, x_f
Fu = Force to control command scaling
fut = Future
i = value for time index, as in $i\Delta t$
NN = Neural Network (implies static)
p = Predicted
s = Slow, as in slow states, x_s

INTRODUCTION

Every vehicle system has limits, whether we realize and understand them or not. In the past (and even today for newly discovered limits), overcoming or avoiding limits was an art, conquered by the individual aviator. As the field of aerospace engineering grew, so did the awareness and understanding of limits' origins, importance, and urgency. Limit protection (or elimination) grew into a science. When the operator drives the system beyond its limits, the results are unpredictable and include some sort of loss, such as wear, damage, destruction, injury, or death. Limit protection systems were designed to interact with elements of the overall flight control system. Those elements include the pilot's maneuver & trajectory planning, his bodily reactions, the display system, the inceptor system, the flight control system, the actuators, and the aerodynamic design of the vehicle itself. These limit protection elements have been successful, but typically attempt to interact with fixed elements along the control command path. For example, the protection system might be the conscious restraint of the pilot, but this compromises speed and adds the risk of human error, variability, and uncertainty.

The purpose of a limit protection system is literally to prevent the aircraft from violating its limit boundaries. Conservative safety constraints can do the same. But safety constraints restrict the performance of the vehicle. Safety and performance are typically in opposition. The true value of a limit protection system is the reduction of the safety versus performance compromise.

OPEN PLATFORM FOR LIMIT PROTECTION

The Open Platform for Limit Protection presented here is the definition and description of functional structures and their outputs (deliverables). It is presented as a template that will structure and facilitate the design and prototyping of limit protection systems. It can be implemented in a variety of commercial tools for control systems design, including MATLAB/Simulink[1] and Advanced Real-Time Control Systems[2]. The intent of the OPLP is to balance the design freedom needed by the control systems designers with the practical functionality required for a system with potentially multiple cues and multiple control loop interfaces. The structure of this platform was chosen to accommodate prior and ongoing research and foreseeable future control systems theory and applications. This chapter defines this OPLP template and explains where and how the prior art fits into this platform. The succeeding chapter documents several limit protection systems designed, prototyped, and tested in the context of this platform.

This Open Platform for Limit Protection (OPLP) adopts a holistic approach for limit protection and imposes protection constraints at appropriate points across the control path as shown in (Figure 1). Limit protection is present in the total vehicle control loop within each of these elements, traditionally and primarily in the deliberate control and conscious restraint that the pilot exercises during flight. The force-feel system of the inceptor has physical limitations of stiffness, damping, inertia, and nonlinear artifacts such as dead band, hysteresis and so on. Commonly in modern complex aircraft such as the V-22, the JSF, and the F-22 mentioned earlier, the vehicle's Flight Control System (FCS) is designed with integral or "built-in" protection for significant foreseeable limits. Forward of the FCS, control surfaces and actuators; whether hydraulic or electrical; have limit protection mechanisms such as overpressure valves, blow-out gaskets, droop stops, and circuit breakers. And the vehicle itself may have limit protection integral to its aerodynamic design, such as canard designed to stall before the main wing. These are the common methods of limit protection today: limit protection integral to each control subsystem or element in the control loop.

In Figure 1, the Open Platform for Limit Protection is boxed with the dashed line. Its development grew from a design for limit avoidance solely through voluntary (overrideable) tactile cues. But, as was found in the HELMEE research[11] and again during prototyping of the blade stall cue described in the next chapter, such cues worked best when combined with corroborating visual cues. Moreover, there were instances when the limit protection tactile cue was too rapid for the pilot to follow, felt jittery, and suggested the need for automatic or autonomous protection for faster, high frequency limit avoidance. Consequently, an open design for tactile cueing[3] was extended to encompass limit protection across the control loop. The solid signal lines in the figure represent the elements of the platform that have been prototyped and tested with this thesis. The blocks and signals indicated with dashed lines represent envisioned logical extensions to the approach that are yet unrealized.

Among the modules, information flows in one direction only, allowing a decoupled set of replaceable subsystems and an open platform that can be easily renewed and extended. There are three levels of functional modules for: 1) limit prediction and critical control calculation, 2) limit cue arbitration and distribution, and 3) control loop interface. The first module, Limit Prediction and Critical Control Calculation, may be considered two separate functions. But in practice, their algorithms need to be tightly coupled and they form an integral module that provides both functions. Likewise, the second major module treats limit arbitration and distribution together as integral functions in one module. The third module is actually a class of modules that have the common function of influencing the vehicle control loop, but do so in different ways using different signal interfaces.

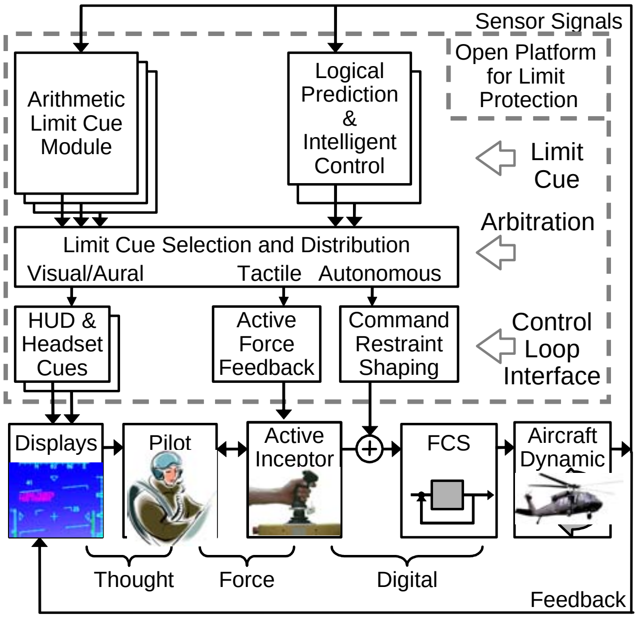

Figure 1: The OPLP Holistic Approach

Nature of the Limit

When designing a limit protection algorithm, the limit itself is usually given rather than chosen. As the nature of the limit is understood, the appropriateness of the remaining design choices becomes clear for the design of the limit cue module and for the later Arbitration and Control Loop Interface modules. Considerations of the limit are shown in (Table 1) with examples from a continuum of possibilities.

Knowledge

When a new phenomenon (such as a vehicle limitation) is discovered, the operators, designers, and society at large, progress through stages of technological knowledge about that phenomenon. It is a progression through ignorance, awareness, measurement, and ultimately, fine control. These stages of technological knowledge[4], shown in Table 2, guide the design choices for a limit cue module and its output, the limit cue itself.

For example, when technological knowledge reaches the pre-technological stage (stage 3) where at least some basic "rules of thumb" are known about when the limit margin improves and which control inceptors affect it positively or negatively, then these rules could be built into a basic logical limit cue. When the limit itself can be defined (i.e. the maximum or minimum value) and measured (stage 4), then at least an alert cue can be used. As more complete knowledge is gained, the dynamical nature of the limit is characterized. Then (after stage 5), the limit can be predicted and the critical control positions determined so that a constraint cue may be used.

Table 1. Nature of the Protected Limit

Consideration	**Possibilities**	**Limit Examples**
Knowledge	Control the mean	Power Settling
	Process Capability	Pilot Induced Oscillation
	Characterized Process	Engine Torque
Origin	Aerodynamic	Rotor Blade Stall
	Structural	Engine torque
	Controllability	P.I.O.
	Regulatory	Assigned altitude
	Physical	Terrain, Obstacle
Time Frame	Instantaneous	Eng. Overspeed
	Reflexive	Vertical Load
	Cognitive	Acrobatic attitude
Risk	Soft limit	Engine Temp.
	Hard limit	Max Flapping

Table 2. Stages of Knowledge

	Name	Character	Typical Forms. Locations
1	Complete Ignorance		None. Nowhere.
2	Awareness	Pure Art	Tacit. In user's head.
3	Measure	Pre-technological	Discussed. User community.
4	Control the Mean	Scientific method is feasible	Written & hardware. Gross control.
5	Process Capability	A solution found. Local "recipes"	Hardware manuals. proprietary designs.
6	Process Character	Tradeoffs & Optimization	Empirical equations Databases.
7	Know Why	Science	Analytical solutions. Textbooks, libraries.
8	Complete Knowledge	Nirvana	Absolute Omnipresent

Source: Adapted from Bohn4.

When new limits and phenomena are first recognized, their gross qualities are learned and aviators adapted their mission planning and maneuvering to accommodate them. After more rigorous research, engineers are able to design control systems for the new phenomenon. In the first case, limit protection requires human knowledge and involvement, perhaps through a cockpit visual or aural display. In the later case, the knowledge is captured in a limit protection system that can drive tactile cues or automatic protection. An advanced stage of knowledge is a prerequisite to greater understanding of the nature of the limit's origin, time frame, and risk.

Origin

But whether given or chosen, vehicle limits ultimately trace to one of a few characteristic origins. Structural limits, for example, commonly have numerical handles – they can be monitored through sensor measurements of stresses, strains, forces, and accelerations. In contrast, while some controllability measurements (limits) are defined numerically (ex. ADS-33 [5] limits on pitch (roll) oscillations), others are qualitative or pseudo-quantitative, (ex. Cooper-Harper handling qualities levels).

Time Frame

The time frame (as described with regard to Table 1) of limit protection action also guides design choices with regard to where and how the limit should be protected. The system designer should consider whether the limit is so volatile and fast that it would require practically instantaneous, autonomous limit protection, or whether it is slow enough for voluntary protection within pilot workload and useable cue environment, and so could be presented as a visual or tactile cue.

Risk

Finally, when considering the nature of the limit, the risk of limit violation guides some design choices. Depending upon how a structural limit is defined, it may be the ultimate load limit of a vehicle component or, more likely, a conservative value accounting for fatigue wear and the uncertainties of design and use. When the consequences of limit violation are severe or catastrophic (a so called "hard" limit), then the designer may choose to protect the limit autonomously, without allowing the pilot to override the protection. If the consequences are not catastrophic, but instead are fatigue wear and reduced component life, then more liberty may be afforded to voluntary limit cues for the pilot.

Limit Cue Module Design

Limit Protection and Critical Control Calculation are two functions that, in practice, are so interdependent and tightly coupled that they need to be designed as an integral module. There may be many limit cue calculation modules in the OPLP using disparate sources as inputs. For example, there may be a hub moment limit module that uses instrumentation signals from sensors attached directly to parts of the transmission, or there may be a vertical load limit module that monitors a common avionics data bus for the information it needs. The character of the input information is left open to allow flexibility for the limit prediction algorithm designers. As new aircraft are designed, its creators may foresee the need to protect particular limits and build the requisite sensor telemetry into the aircraft's Vehicle Management System (VMS) or Health and Usage Monitoring system (HUMS). In these cases, the limit prediction modules may share identical or common information interfaces with the VMS or HUMS. When the need for limit protection is identified for pre-existing aircraft, the limit prediction module may use pre-existing VMS/HUMS information if available, or may use instrumentation added to the aircraft in an ad hoc fashion and dedicated to the limit protection.

The internal design of the limit cue module's limit prediction and critical control calculation algorithms presents design choices for limit prediction and avoidance algorithms (listed in Table 3). The design choices can be characterized by the ultimate limit they address, the type of prediction uses, the mechanism used in the limit modeling algorithm, and the method of calculating the corresponding critical control position. Limit prediction has relied on analytical methods, labeled here as "Arithmetic", whereby the vehicle limit is given a numerical handle. This handle may be a direct sensor measurement, such as airspeed or vertical load, or it may be found indirectly from related measured parameters. Some limits may have no implicit numerical handle but are given a number with a correlation function. Main rotor blade stall is an example where an empirical value, Equivalent Retreating Indicated Tip Speed (ERITS), provides a convenient correlated numerical value. But besides arithmetically based cues, this thesis acknowledges "Logical" limit cues that are understood through known or suspected cause and effect relationships and rule-based heuristics. The limit protection control cues may also be heuristically determined. This approach brings emergency conditions and emergency procedures within the realm of limit protection.

Table 3. Limit Cue Definition and Design Choices

Module	Aspect	Choices	Definitive Applications
(Arithmetic) Limit Cue Prediction	Type of Limit Prediction	Fixed Time Horizion	UH-60 Engine Torque[11]
		Dynamic Trim	XV-15 Angle of Attack[12]
		Peak Response Estimation	UH-60 Hub Moment[6,7]
	Prediction Mechanism	Math Model	AH-64 Energy Mgt,[8]
		Static Neural Network	UH-60 Blade Stall
		Adaptive Neural Network	UH-60 Blade Stall [9]
	Critical Control Calculation	Inverse Gradient	UH-60 Blade Stall
		Pseudo-Inverse	XV-15 Angle of Attack
		Weighted Pseudo-Inverse	None
		Algorithmic Search	UH-60 Hub Moment [6,7]
	Type of Cue	Constraint	UH-60 Rotor Blade Stall
		Alert	UH-60 Rotor Blade Stall
		Transfer Function	Pilot Induced Oscillation [10]
		Friction	Pilot Induced Oscillation [10]
(Logical) Limit Cue Calculation	All the above listed options of arithmetic cues are available.		
	Prediction and Control	Crisp IF-THEN	None
		Fuzzy Inference	Pilot Induced Oscillation[10]

Note: Underlined references refer to limit cues first developed within this OPLP

Arithmetic Limit Cue Design

Arithmetic cues rely on a state space dynamical *aircraft model* to represent the system of aircraft states, inputs, and outputs.

$$\dot{\mathbf{x}} = g(\mathbf{x},\mathbf{u}) \qquad \mathbf{y} = h(\mathbf{x},\mathbf{u}) \qquad (1)\ (2)$$

The *state*, x, is a defining set of aircraft motion characteristics and the *input*, u, is the vector of physical displacements of the cockpit controls. With information about the states and the controls, and an accurate model of the dynamic interaction between them, the mathematical solution provides the future state of the aircraft. The limited parameters (or *limit vector*), y, is a vector of individual limits, y_i , each of which is an algebraic function of the present states and inputs. Often, a limit parameter is identical to the value of a state.

Depending on the context, the word *limit* may refer either to the name of the limited parameter (such as Vertical Load or Airspeed) or to a critical value of that parameter (such as 4 G's or 150 Knots). The *future limit margin* is defined as the difference between the limited parameter critical value and the value of that parameter at some future time.

$$\Delta y^{+}_{\mathrm{fut}} = y_{\mathrm{lim}} - y_{\mathrm{fut}} \qquad \Delta y^{-}_{\mathrm{fut}} = y_{\mathrm{fut}} - y_{\mathrm{lim}} \qquad (3)\ (4)$$

A *control*, also called an *inceptor*, is the physical lever that is the interface between the pilot's applied forces and displacements and the Flight Control System's information medium. The *control margin* is defined as the difference between the present control position and the *critical control position* where, if the pilot displaced the controls to that position, the aircraft would reach the critical limit value, *the limit*. A limit may be a function of the control configuration and flight condition, $y_{lim}(x,u)$, but usually it is a constant maximum or minimum allowable value. A *limit* has a corresponding *upper control margin* when there exists a *critical control position* greater than the present control position. Likewise, a limit has a *lower control margin*, when there exists a corresponding *critical control position* less than the present control position. By convention, whether referring to maximum limits or minimum limits, limit margin and the control margin are both considered positive while the system is within the limit boundary.

$$\Delta u^{+} = u_{crit} - u_{o} \qquad \Delta u^{-} = u_{o} - u_{crit} \qquad (5)\ (6)$$

The relationship between the *future limit margin* and the present *control margin* is non-causal, non-linear, and non-bijective. To establish a causal relationship and enable practical limit avoidance cueing, every limit prediction model makes a *future transition assumption* for each limit. With this assumption, the present aircraft state, x_o, and the control position, u_o, a limit prediction model provides a *predicted limit vector*, $y_p(x_o,u_o)$, or *predicted limit*, y_{ip} . The *predicted limit margin* is defined as the difference between the *predicted limit* and the critical limit value or *limit*.

$$\Delta y_{i\,\mathrm{p}} = y_{i\,\mathrm{lim}} - y_{i\,\mathrm{p}} \qquad (7)$$

In a limit avoidance cue, the cueing system approximates a mapping between the *predicted limit margin* and the *present control margin*. This mapping of a predicted limit to the critical control position is the essence of effective limit avoidance tactile cueing.

Limit Prediction Type

The defining differences among the types of limit predictions are the assumptions about their system's transition from the present to the future. The fixed time horizon prediction calculates the value of the limit parameter at a fixed distance in the future. In this case, the future transition assumption is an assumed future time history for the controls. The dynamic trim prediction, calculates the limit parameter value for the aircraft dynamical system in a quasi-steady equilibrium. The future transition assumption in this case, is an assumed transition for the states.

Fixed Time Horizon (FTH)

This type of prediction assumes that the controls will follow some defined path to a chosen point in the future. The fixed time horizon prediction may assume the controls follow the worst-case path. More commonly, the controls are assumed to follow a path similar to the path followed by the pilot during actual or simulated test flights that provide time history data. The fixed time horizon method maps the relationship between the vector of states and controls at each time, t_o, to the limit value at time, $t_o + \Delta t$. This mapping can be captured in any number of ways, most effectively in neural networks as described below. The advantage of this method is that the time frame for the prediction is known and, depending on the nature of the limit, can be reasonably accurate to a few tenths of a second or more into the future. For example, the limit predictions of the HELMEE study used time horizons (Δt) of 0.25 to 0.46 seconds [11].

$$\begin{tikzcd}
\begin{bmatrix}\mathbf{x}(t_o)\\ \mathbf{u}(t_o)\end{bmatrix} \arrow[d, "\mathbf{h}"'] \arrow[drr, dotted, "\mathbf{f}"] & \cdots & \begin{bmatrix}\mathbf{x}(t_o+\Delta t)\\ \mathbf{u}(t_o+\Delta t)\end{bmatrix} \arrow[d, "\mathbf{h}"'] \arrow[drr, dotted, "\mathbf{f}"] & \cdots & \cdots \\
\mathbf{y}(t_o) & \cdots & \mathbf{y}(t_o+\Delta t) & \cdots & \mathbf{y}(t_o+2\Delta t) \quad \cdots
\end{tikzcd}$$

$$\mathbf{y}_{pFTH} = \mathbf{f}(\mathbf{x},\mathbf{u}) \tag{8}$$

These prediction times are far enough to give the pilot time to react, but not so far that the prediction loses accuracy. More distant time horizons loose accuracy due to pilot self-determination. That is, the pilot is likely to choose a future control path unlike control path of the aggregate training data for the prediction model.

Dynamic Trim (DT)

The dynamic trim prediction[12,13] separates the n aircraft states into k "slow" states that vary slowly with time, and (n-k) "fast" states that vary quickly and reach a steady value during a maneuver.

$$\mathbf{x} = \begin{bmatrix}\mathbf{x}_{slow}\\ \mathbf{x}_{fast}\end{bmatrix} \in R^n \qquad \mathbf{x}_{slow} \in R^k \quad \mathbf{x}_{fast} \in R^{n-k} \tag{9}$$

The future transition assumption is that the controls and the predicted slow states do not change while the fast states have changed and settled to a constant. The predicted limit follows from the solution to the dynamical system (1) and (2) in the form:

$$\begin{bmatrix}\dot{\mathbf{x}}_{slow}\\ 0\end{bmatrix} = \mathbf{g}(\mathbf{x},\mathbf{u}) \text{ , } \quad \mathbf{y}_{pDT} = \mathbf{h}(\mathbf{x},\mathbf{u}) \qquad (10\ )\ (11\ )$$

The manner in which the fast states transition to steady and the time they take is irrelevant to the method. Consequently, the prediction time is not defined. In practice, the dynamic trim solution can be difficult to find for complex dynamical models, but an adaptive technique [14] can approximate the dynamic trim prediction model from time history *a posteriori*.

The dynamic trim prediction is well suited for limit variables that reach their maximum or minimum values in quasi-steady state. It gives good predictions for the worse case limit values possible during a maneuver. While the prediction time horizon is undefined, this characteristic is generally evident from inspection of the time history of the prediction and the actual limit value.

Prediction Mechanism

Math Model

This prediction method uses a model for predicted limit, y_p, derived from *a priori* understanding of the aircraft dynamics.

$$\mathbf{y}_p = f(\mathbf{x},\mathbf{u}) \tag{12 }$$

This method solves the state equation (1) based on the future transition assumption. For the dynamic trim prediction, the assumption defines values for the fast states and assumes the controls are held at the current position during the maneuver. For the fixed time horizon prediction, the assumption defines the control future time history. The one special form of the math model that requires no future transition assumption is the zero time horizon prediction, which is not a prediction at all. In that case, the present limit is used as the prediction, y_p=y. The math model produces a virtual table of limit predictions for given states and control values. This can take the form of an actual look-up table for use with multiple argument interpolation, but more commonly this prediction method is a preliminary step to create neural network training data.

Static Neural Networks

An artificial neural network is a mathematical construct, such as a polynomial or a combination of vector functions called basis functions (such as the sigmoid, tan-sigmoid, and radial basis functions). Based on error back-propagation, this construct has parameters that self-adjust to provide a target output. Neural networks capture the *a posteriori* relationship between the controls and the predicted limits based on representative pattern and target data. Math model solution sets can provide this data directly or the time history data from flights and simulations can provide it. Static network training is completed with all the data available at once.

$$y_p(t) = f_{NN}(\mathbf{x}(t), \mathbf{u}(t)) \qquad (13)$$

Type	Training Patterns				Training Targets
Dynamic Trim	$x_{slow}(t), u(t)$	→	$f_{NN}(x,u)$	←	$y_{DT}(t)$
Fixed Time Horizon	$x(t)$, $u(t)$	→	$f_{NN}(x,u)$	←	$y(t+\Delta t)$

Prediction error is a common practical difficulty with math model and static neural network predictions because aircraft parameters and flight conditions change, as when the center of gravity shifts or pilot control characteristics change. The HELMEE and HACT projects correct prediction errors using complementary filters that effectively eliminate steady state prediction errors. But while this technique performs an essential function, the filters cloud the output from the prediction model.

Adaptive Neural Networks

Adaptive neural networks offer an alternative method to correct real time prediction errors and, unlike filters, they improve the prediction function to capture local or transient variations in the dynamical relationship of states, limits, and controls[14]. Unlike a static network, an adaptive network adjusts the neural network weights incrementally, as additional pattern and target pairs are presented. In other words, the adaptive neural network uses time history data in real time to reduce the prediction error and improve the prediction model. In order to use an adaptive network to approximate the predicted limit, it must have a measured or inferred value for the limit parameter to use as its real time target.

Critical Control Position

When the limit parameter is adequately understood, the limit cue module can establish a relationship between a limit and the controls. Local sensitivity methods depend on the limit gradient or the limit vector Jacobian, also called the limit sensitivity matrix. This method approximates a linear limit-to-control relationship using the tangent to the limit surface defined by the math model, $y_p = f(x,u)$, or neural network $y_p = f_{NN}(x,u)$. If the limit prediction function is well understood, the predicted limit Jacobian can be found analytically. If not, the local limit sensitivity is found through perturbation methods, iterating on its limit prediction system as a subsystem or subroutine. For the non-predictive limit models, $y_p = y$, the critical control position equals the current control position, $u_{crit} = u_o$

These methods have the advantage of computational speed. The disadvantages are those inherent in the linearization. The limit surface may be highly nonlinear and local sensitivity values may vary considerably with small changes in the state or control. Also, it is not uncommon for the current control position on the limit surface to lie at a local minimum or maximum where the same limit is reached whether a control is moved one direction or the opposite. Linearization will fail to predict accurate critical control positions for these conditions.

Inverse Partial Derivative

This simple method finds the control margin by dividing the limit margin by the limit sensitivity for each control axis (Figure 2).

$$\Delta u_i = \left(\frac{\partial f_i}{\partial u_i} \right)^{-1} \left(y_{\lim} - y_p \right) \qquad (14)$$

This limit sensitivity method estimates the critical position for each active axis independently. The HELMEE study used this method effectively to cue each limit along a distinct active control axis. But in that study, the sensitivity was set at a constant value that was appropriate and approximately correct for the flight profile of the evaluation.

Pseudo-Inverse of Limit Gradient

An alternative method treats the controls together as a vector and uses the Jacobian's pseudo-inverse to find the control margin vector to the "nearest" control combination that zeros the limit margin. This nearest distance is the least-squared distance of each axis control margin. This method weights each of the controls equally.

$$\Delta u = \left(\frac{\partial f_i}{\partial u}\right)^{+} \left(y_{\lim} - y_p\right) \qquad (15)$$

The critical control position for each axis follows directly from the control margin vector decomposition. This method works fairly well when one limit is moderately influenced by two or more active control axes.

Weighted-Inverse of Limit Gradient

A variation of the previous method multiplies the pseudo-inverse by a weight matrix. This weight vector may be a function of the states to emphasize or de-emphasize control axes at different flight conditions

$$\Delta u = W(x)\left(\frac{\partial f_i}{\partial u}\right)^{+} \left(y_{\lim} - y_p\right)$$

$$x \in R^n,\ u \in R^k,\ W: R^n \to R^{k \times k} \qquad (16)$$

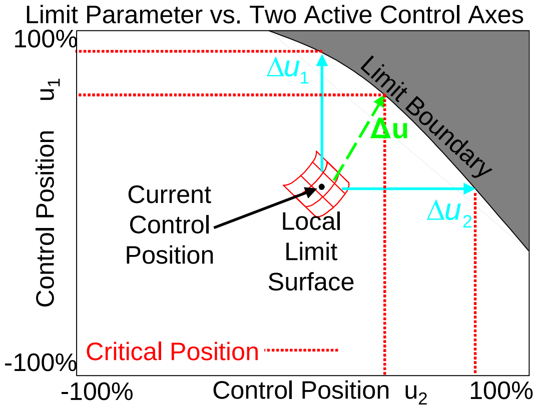

Figure 2. Linear Critical Position Calculations

Algorithmic Limit Search

This approach emerged in two variations for a first order vertical load limit cue and for a transient peak limits of longitudinal. This approach uses an algorithmic surface search algorithm to find the critical control position. This method begins a search at the current state, x_o, and samples the prediction models, $y_p(x_o,u)$, at increasing and decreasing positions for each of the active control axes in turn. Throughout the search, the present (instantaneous) state vector is used. When the resulting prediction for a limit parameter first moves into a set of prohibited values, the control position at that point becomes the critical control position. A prohibited value for the limit parameter is one beyond the maximum or minimum allowable or an internal subset of values. The algorithm finds any critical control positions above or below the current positions of each of the axes.

This method does not necessarily assume a positive or negative relationship between the control and the limit. It does allow the possibility that the non-linear inverse may not be one-to-one. It has these advantages over the local sensitivity methods described earlier. Its chief drawback is its computational demand. Without a capable active control system computer, the designers may need to simplify the complexity of the neural network used for the limit prediction or reduce the resolution of the limit surface search. The latter option is usually best since the prediction is itself only an approximation and there is no need to search to high precision a limit surface of lower precision.

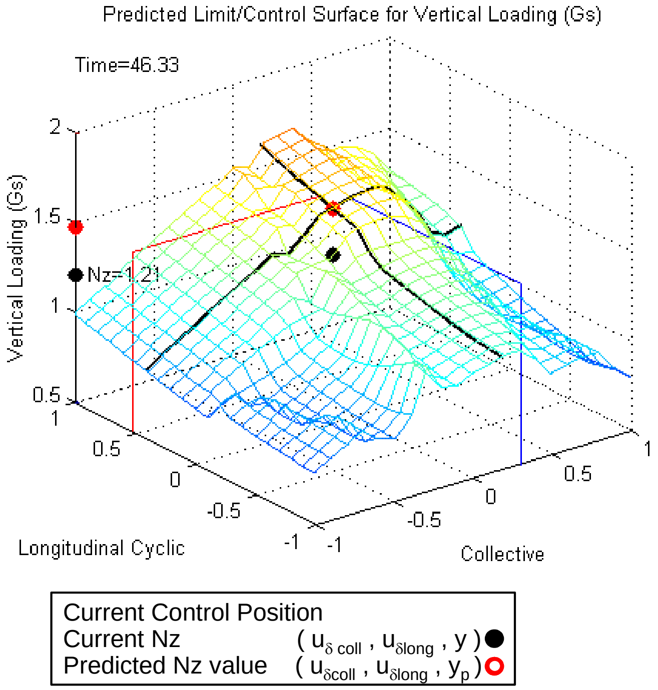

Figure 3. Algorithmic Limit Search (1st Order, 2D).

The Mesh Surface (Figure 3) represents a predicted limit (vertical loading, N_z) with respect to collective and longitudinal control axes. The algorithm treats it as one with a first order response, or at least one where other time values (transient peaks) of the limit parameter are not considered. At the depicted instant in time, during a pull up maneuver, when the control and limit coordinate is positioned at (u_{coll}, u_{long} ,y), the search algorithm begins at the predicted limit for the current control position (u_{coll}, u_{long} ,y_p). The algorithm varies each control position in the prediction function away from the start position, along the admissible control positions shown as black lines. When the prediction exceeds the limit (in this example y_{lim+}= $N_{z(max)}$=1.5), that control position is defined as the critical control positions for each axes for that instant. Those upper critical control positions are indicated in red and blue lines. Note in this example that the predicted limit decreases at very high collective positions. Had the limit been set a little higher (i.e. $N_{z(max)}=1.6$), the algorithm would not find a critical position for collective because no position along the collective search path exceeds the limit.

Logical Limit Cue Design

Logical limit cues rely on rule based decisions. Generally these take the form of logical syllogisms, either the “crisp” logic or “fuzzy” logic. They are effective in detecting both limits and emergency conditions. Logical limit detection can also provide limit cues when the nature of the limit is not yet well understood and the stage of technological knowledge is inadequate to calculate a control constraint.

Crisp IF-THEN logic

The basic Aristotelian syllogism draws a conclusion from two premises. In the context of logical limit prediction or detection, the first premise defines the limit in terms of some function of aircraft states. The second condition reports a related condition during flight. The conclusion determines whether the vehicle is within limits or not, and can trigger limit cue for the pilot or an autonomous limit protection mode. This is the very common approach for visual cockpit indicators of aircraft system status. Such limit syllogisms are hard wired sensor switches that open or close the illumination circuits for cockpit warning indicator panels. Caution, warning, and advisory panel lights for helicopters are commonly provided for engine chip detection, main rotor overspeed, main rotor underspeed, low fuel, main transmission oil pressure, fuel pressure, and so on. An example for an oil pressure indicator lamp takes the form :

Such limit protection cues rely on the pilot to make the appropriate limit protection action or to execute a pre-trained emergency procedure. Alternatively, this type of limit detection logic can trigger task tailored flight control laws to accommodate limit proximity or emergency conditions.

If sensed oil pressure is greater than 120 psi

Then close “High Oil Press.” warning lamp circuit.

Sensed oil pressure is greater than 120 psi.

∴ Close “High Oil Press” warning lamp circuit.

Fuzzy Inference

In contrast to crisp logic, fuzzy logic allows possibilities and degrees of limit violation or emergency condition fulfillment. The aircraft states, controls, and limits become fuzzy variables for a fuzzy inference system. For example, airspeed as a fuzzy variable is not operated on as a numerical value of 60 knots. Instead it is described by membership function such as “cruise speed”, “hover”, or “below ETL”. Likewise, an output, such as collective position, can have fuzzy membership functions such as “forward”, "centered”, or “aft”. Each membership function is a unimodal possibility distribution across a universe of discourse, analogous to a function domain.

A fuzzy inference system follows five steps. First, it fuzzifies the input, converting it from a numerical value into a membership function. Second, it applies the fuzzy operators analogous to the logical AND, OR, and NOT. Third, it applies an implication method. This is a rule described as an IF – THEN relationship. Fourth, the results for all the rules are considered simultaneously and aggregated. Finally, aggregate result is defuzzified to number. The rules are defined from *expert* knowledge such as pilot experience, aircraft technical manuals and handbooks, and aviation textbooks. For example, the rules for an emergency procedure cue are a pilot’s answers to: “What are the indications that make you realize and identify an emergency condition?” and “What do you do to remedy the emergency?” These become fuzzy IF-THEN relationships that infer the logical cue.

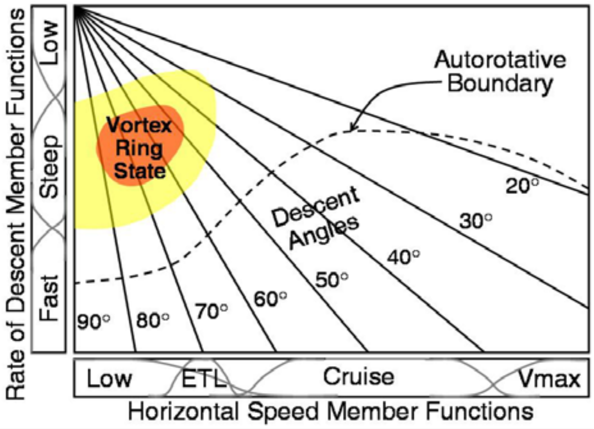

Figure 4. Depiction of Fuzzy Vortex Ring Estimator

As an example, consider settling with power as flight region beyond controllability limits. If the vortex ring state could be well defined as a numerical limit, an arithmetically based limit avoidance cueing system would apply. The HACT Program takes this approach to provide a power settling avoidance cue on the collective control axis[15]. However, when the condition is not explicitly defined but is generally understood, an expert model assesses the possibility of the condition and sets tactile avoidance cues and non-tactile cues. This vortex ring avoidance cue treats the condition not as an arithmetic cue as does the HACT program, but as a logic based cue. While not usually addressed in helicopter operator's manuals, flight schools include settling with power as an important topic of instruction. School manuals[16] describe the conditions conducive to settling with power as: a vertical or nearly vertical descent of at least 300 feet per minute, low forward airspeed, and normal-high engine power (from 20 to 100 percent). From this knowledge, an abridged fuzzy inference system takes a form depicted in Figure 4.

Arbitration Module Design

The Arbitration module performs two major functions (Figure 5): it selects among simultaneous limit cues for each control axis and it distributes limit protection to appropriate points across the control loop. These functions are distinct and may be executed sequentially in either order or simultaneously.

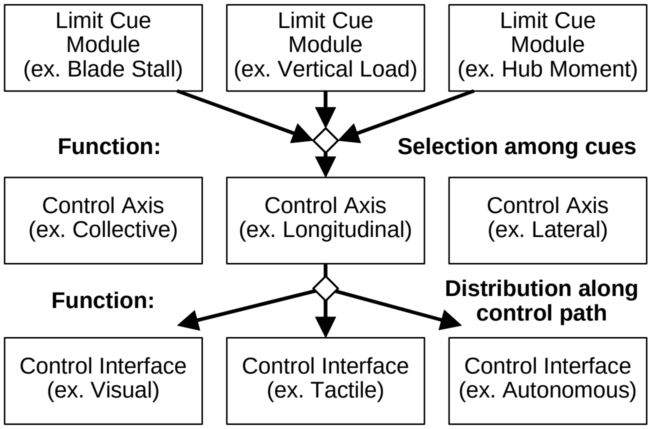

Figure 5. Major Functions of the Arbitration Module

Limit Cue Selection

One-to-One

With multiple limit constraints for each control axis, a limit cue selector is needed to select which will serve as the constraint, which will serve as the alert cue. for each of the active control axes. The module defines the cue position, u_{cue}, which the tactile interface module will use and any control shaping based on the control margin, Δu. For simple limit protection systems with only a few limits, the limit to control axis may be a bijective mapping. This was the approach used for the HELMEE project [11], which mapped engine torque directly to collective and main rotor blade stall directly to longitudinal cyclic. In this case there was no possibility of conflict between the cues.

Table 4. Arbitration Definition and Design Choices

Module	Function	Choices
Arbitration	Limit Cue Selection	One-to-One
		Most Conservative
		Intelligent Selection
	Control Loop Distribution	Fixed
		Frequency Distribution
		Deadband Shaping

Most Conservative of Several Limit Cues

For systems with multiple control axes - each with multiple limit cues - the most conservative cue for each control axis may be used. For example, consider a moment of forward flight when the longitudinal cyclic position is forward at -5%. The Critical Control Positions for two limits are 30% aft for vertical load limit and 45% aft for the main rotor blade stall limit. The most conservative method chooses 30% aft as the combined critical control position.

Intelligent Selection

But it is not always appropriate to cue every control for the most conservative limit. At times the cues may conflict with one another as when one limit is exceeded because a control axis is too far left while another limit is exceeded because the same control is too far right. In such cases, the arbitrator may need a rule-based method of de-confliction and appropriate cue selection. In cases when the aircraft flies beyond two or more limits simultaneously, the limit cue constraints may be in conflict. For more complex systems, intelligent control algorithms with decision heuristics may be needed in the Arbitration module to deal with multiple conflicting cues and assign precedence among cues based on the flight environment and control mode. The rules that resolve this conflict rely on the knowledge of interrelated limits and the consequences of control movements. Examples of interrelated limits are vertical loading and main rotor blade stall. The arbitration module must select the most urgent limit for autonomous protection or a tactile cue, or it must elevate that conflict decision to the pilot through a visual or aural cue.

Distribution to Control Loop

The design for limit protection distribution relies heavily on an understanding of the nature of the limit, particularly the risk of limit violation and the timeframe required for protection actions. Autonomous limit protection can be made as rapidly as its flight control hardware can operate, often at 50 Hertz update rate and greater. Tactile force feedback cues are limited by the reflex reaction time and physical dynamics of the limb-manipulator system, on the order of 0.1 to 1.0 seconds. Visual and aural cues that require cognitive processing, especially textual and verbal cues, require still more time, nearly a second or more. In maneuvering flight, limit parameters are dynamic and, at times, their corresponding control constraints may move rapidly. When driving visual cues (i.e. Heads Up Display readouts), the limit display may be changing too rapidly for the pilot to discern and accommodate. Extreme constraint volatility may also exceed the physical bandwidth of the limb-manipulator system or lead to a force feedback cue that degrades handling qualities and that the pilot finds objectionable.

Fixed

Nearly all current limit protection systems were designed to interface at fixed points in the control loop. For example, the stall warning buzzer common in general aviation aircraft is fixed as an aural display and does not manifest as a visual or tactile cue. In modern cockpits, the cockpit display subsystem may present a visual "pop-up" limit cue accompanied by an aural warning tone. But these would not autonomously protect the limit. They remain visual or aural. The carefree handling systems in complex aircraft autonomously protect critical, fast limits such as rotor yoke bending and drive shaft torque.

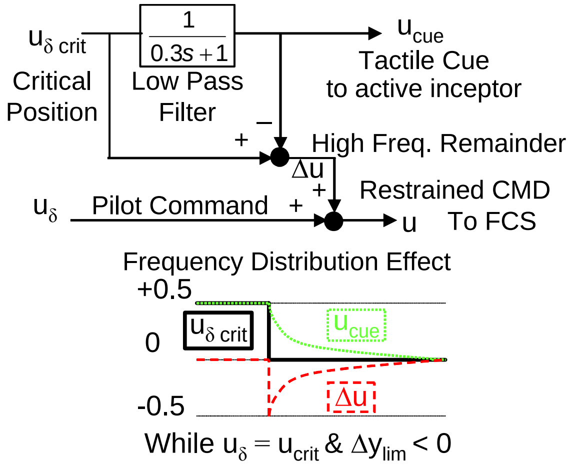

Figure 6. Frequency Based Distribution

Frequency Distribution

The frequency distribution approach (Figure 6) splits limit protection between tactile cues and autonomous protection based on frequency content of the constraint. A low pass filter can slow a volatile tactile constraint cue to a speed where it is acceptable to the pilot, but such a filter adds an effective delay that offsets the advantage of limit prediction. By using the high frequency remainder for autonomous limit protection, the system still provides voluntary tactile avoidance cues for the pilot while automatically protecting the system against high frequency limit constraints. In addition to or instead of a low pass filter shown in the figure, a rate limiting element may be used to slow the speed of a tactile cue. The figure depicts the concept as it would apply to an upper constraint limit that the pilot is flying along or beyond. There would be some additional logic (not shown) that would set whether this frequency distribution feature is active or disabled based on whether the physical pilot command is within the limit boundary.

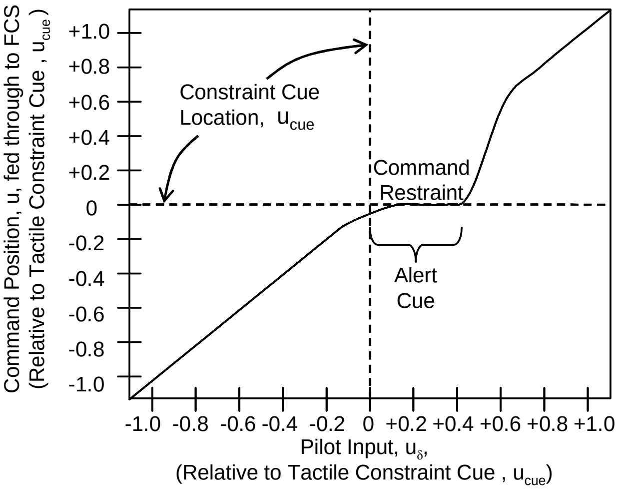

Figure 7. Deadband Split

Deadband Split

Another approach[i] to cue distribution applies a deadband split (Figure 7) to the nominal position command signal (that is, the physical position of the inceptor, u_{δ}) at the location of a limit protection constraint. The fed-through, post-inceptor, FCS input, u, is initially restrained as the pilot pulls through the location of the tactile constraint cue. While the fed through command is restrained, an alert cue is active.

Control Interface Module Design

The pilot has senses for vision, hearing, and touch as already described. Additionally, human pilots have proprioceptive and vestibular senses of accelerations. Forward of the human element, a limit protection can alter the post-inceptor command. Still other limit protection controls are available prior to flight in mission planning and

---

[i] Concept proposed by Nilesh Sahani and Dr. Joseph Horn of Pennsylvania State University.

forward of the pilot in the flight control system and the control surface actuators. These possibilities are discussed briefly here, with special emphasis on the tactile force feedback interface, which is the crux of the applied research of this thesis. The Control Loop Interface is the last module of the Open Platform for Limit Protection with the design choices listed in Table 5. As such, the module outputs are specific to aircraft subsystems and are not standardized like the two information interfaces internal to the OPLP.

Table 5. Control Interface Design Choices

Module	Aspect	Choices
Visual	Size & Shape	Vision sector
	Symbols	Alphanumeric, Icon, …
	Color	Red, Yellow, Green, …
Aural	Non-Verbal	Direction (left or right)
	Verbal	Intensity (Loudness)
Tactile	Force Feedback $\left(\begin{matrix}\text{for each}\\ \text{control axis}\end{matrix}\right)$	Softstops
		Detents & Gates
		Shakers
		(Bobweight) Dynamics
		Friction (Dynamic & Static)
Command Shaping	Command shaping	Subtract/Add control margin

Visual

Vision is the greatest conduit of information that pilots possess and it is the primary source of information regarding aircraft systems and limits. As a channel for limit protection cues, vision displays offer multiple cues for both simple and complex information. The size of a limit cue is its potion of the visual field of view. The cue can assume various shapes, such as the sector arcs of analog gauges. Particular shapes, such as letters and numbers, are symbols that can carry very detailed information about limits and controls, however, the additional cognitive processing step of interpreting symbols and strings of symbols (i.e. words) adds a small delay to the control process. Color is commonly used to indicate an alert status or urgency. The notable examples are: green to indicate nominal range, yellow to indicate a transient limit, and red to indicate a maximum or minimum peak limit. Visual displays may also provide cue information through both stereoscopic and ocular focal distance.

Aural

The sense of hearing also has a high capacity for information that can be presented from different sides (left or right), at different frequencies (high pitched to low pitched), and at different intensities (quiet or loud). This information may be simple, non-verbal tones or tonal compositions with a remarkable capacity for eliciting emotional reactions such as peace or alarm. The aural analogues to visual text messages are the verbal messages that can carry likewise carry detailed systems and limit information at the cost of additional cognitive processing time. Verbal cues may be masculine or feminine and can carry emotional content.

Tactile Cues

The sense of touch encompasses many distinct sensations potentially useful as limit cues. The inceptor surface *texture* may be smooth, fuzzy, prickly, wet, sticky, etcetera. Active texture cues may be used to communicate such things as the aerodynamic performance of aerodynamic surfaces (laminar versus turbulent boundary layers). The *shape* of the cockpit control levers is commonly used as an identification tool in cockpits. Active shape changing inceptors have been used to provide flight control and limit cues (ex. Angle of Attack cue using a handgrip protrusion[17]). An active heating and cooling element, an inceptor could use temperature to intuitively communicate temperature related limits and system performance such as engine turbine temperature or rotor blade icing. Mild shock may be a useful as a limit alert cue.

The primary forms of tactile cue considered for this limit protection platform are the force-displacement cues of an active cockpit inceptor. Force-feel characteristics, physical control dimensions, and cockpit placement have been the subject of many studies. Depending upon its design capabilities, an active inceptor can generate a counter-force function based on the inceptor position, on time, and on higher dynamical states of the inceptor and the vehicle. The cue force is a combination of the nominal force displacement curve, softstops, the detents, oscillations, damping and natural frequency response. Because human pilots have different degrees of strength and control for the different control axis, it is appropriate to decompose this function into its active control axis components and tailor them to pilot physiology.

$$F = F_{nom} + \sum_i F_{ss\,i} + \sum_j F_{\det j} + F_{\omega} + F_{\omega_n \zeta} + F_{fric} \tag{17}$$

Nominal Force-Displacement Relationship (F_{nom}*)*

An inceptor uses a nominal force-displacement relationship where the pilot feels a centering force that increases gradually and nearly linearly as it is pushed away from its neutral position.

$$F_{nom} = F(u) = k_f(u - u_0) \qquad (18\,)$$

The zero-force intercept is the neutral position where the inceptor will settle when left untouched. An active sidestick can offer cues and guidance by changing the zero-force position and how the counter-force increases as pilot applies force. The force-displacement relationship can be nearly flat, $k_f = 0$. This is the typical feel of a traditional helicopter cyclic stick without friction. Another relationship uses a preload force. With a preload, the control will not move from the neutral position until the breakout force is reached. The force gradient is the key parameter used to dimensionalize the limit protection cues generated by the preceding limit protection modules. a normalized non-dimensional cue (such as constraint height of $\Delta h_{cue} = 1.33$) is multiplied by the stick force required for maximum static deflection (30 Newtons) to arrive at the softstop height (40 Newtons).

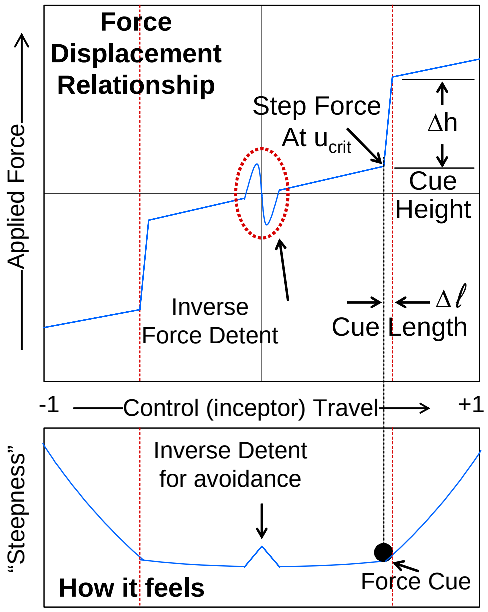

Figure 8. Step Force Softstop with Gate

Step Force at Critical Control Position (F_{ss}*)*

Another successful form of softstop uses a step increase in counter-force at the critical control position (Figure 8). The cue provides a precise indication to the pilot about the location of the edge of the flight envelope defined by the limit prediction algorithms. However, when the critical control position varies rapidly while the pilot is following the cue, it can seem jittery and may be objectionable.

Detents and Inverse-Detents (F_{det}*)*

A force detent superimposed on the nominal force-displacement relationship serves well as a trim cue or an autopilot cue. The sidestick will remain in a detent "force-well" until the pilot provides a sufficient break away force. Then the stick would follow the nominal force-displacement relationship. The inverse detent, also called a tactile gate, has the opposite effect (Figure 8). It pushes the stick away from the inverse-detent position to one side or the other. Such a cue can steers the pilot away from high-risk flight conditions, such as very steep, high power approaches where vortex-ring state is predicted as imminent.

Shaking and Vibration ($F\omega$*)*

Shaking and vibration is a very useful supplemental cue. It is used to indicate that the aircraft is already beyond a limit. It can also cue impending limits whose indications involve vibration. For example, a high frequency vibration can cue loss of tail rotor effectiveness and tail rotor malfunctions. A low frequency, 1/rev, can cue main rotor stall and other main rotor limits.

$$F_{\omega} = F(t) = A\sin(\omega t) \qquad (19\,)$$

Dynamical Response ($F\omega_n\zeta$*)*

The frequency response of an active inceptor can imply agility or sluggishness to convey the maneuvering capability of an aircraft in varying flight regimes. Damping as a force cue, can be very effective for transient limits such as maximum flapping with respect to cyclic. It is the only force cue listed here that depends directly on control speed. Maximum transient limits depend primarily on fast control movements rather than control positions.

$$F_{\omega_n \varsigma} = M(\ddot{u} + 2\omega_n \varsigma \dot{u} + \omega_n^2 u) \qquad (20\,)$$

Friction (F_{fric}*)*

Friction is a constant force that opposes the direction of movement. It may have use as a cue, but mainly it helps the pilot hold the control at a constant position despite airframe vibrations or those occasions when the pilot removes his hand.

Control Restraint Shaping

The inceptor serves as an interface between the physical world where the pilot resides and the digital domain where the flight control system operates. Command restraint shaping is a form of autonomous limit protection where a portion or all of the control margin is added or subtracted to the post-inceptor command signal when a limit violation is predicted. The "restrained" command signal becomes the input for the flight control system.

CONCLUSION

The Open Platform for Limit Protection adopts an open engineering systems approach to the guide the design of limit protection systems. A carefree maneuver system that adopts the OPLP structure uses well defined functional modules and standardized information interfaces. Information flows in one direction through the OPLP modules, allowing them to remain decoupled. This facilitates the addition and replacement of new limit modules and extensibility to new control loop interfaces. The OPLP approach simplified the creation and combination of the carefree maneuver applications described herein. The standardized information interface facilitated the parallel development and integration of limit protection cues.

In the process of developing the modular structure of this platform, the design of modern limit protection system was analyzed and the taxonomy of functions, means, methods, and mechanisms was cataloged. The lists and descriptions of design choices within this document are not exhaustive, but define the scope of options and suggest a systematic approach for limit protection control systems design to replace ad hoc or generic control systems design methods.

ACKNOWLEDGMENTS

This work is carried out under grant NAG 2-1418 originating from the Army/NASA Rotorcraft Division at Ames Research Canter.

REFERENCES

1 The MathWorks [Online], May 2004. Available: http://www.mathworks.com/products

2 Advanced Realtime Control Systems, Inc. [Online], September 2003. Available: http://www.arcsinc.com.

3 Jeram, G., "Open Design for Helicopter Active Control Systems," Proceedings of the American Helicopter Society 58th Annual Forum Proceedings, Montreal, Canada, June 11-13, 2002.

4 Bohn, R., "Measuring and Managing Technological Knowledge," Sloan Management review, Fall 1994.

5 anon., "Handling Qualities Requirements for Military Rotorcraft," U.S. Army AMCOM Aeronautical Design Standard, ADS-33D-PRF, May 1996.

6 Horn, J.F. and Sahani, N., "Detection and Avoidance of Main Rotor Hub Moment Limits on Rotorcraft," AIAA Journal of Aircraft, Vol. 41,(2), March-April 2004, pp.372-379.

7 Sahani, N., Jeram, G., Horn, J., Prasad, J.V.R., "Hub Moment Limit Protection Using Static Neural Networks," Proceedings of the American Helicopter Society 60th Annual Forum, Baltimore, Maryland, June7-10, 2004.

8 Einthoven, P., Morse, C., "Energy Management," Proceedings of the American Helicopter Society Crew Systems Design Specialists Meeting, Philadelphia, PA, October 9-11, 2002.

9 Unnikrishnan, S., Jeram, G., Prasad, J.V.R., "Tactile Limit Avoidance Cueing Using Adaptive Dynamic Trim," Proceedings of the American Helicopter Society 60th Annual Forum, Baltimore, Maryland, June7-10, 2004.

10 Jeram, G., Prasad, J.V.R., "Tactile Avoidance Cueing for Pilot Induced Oscillation," American Institute of Aeronautics and Astronautics Atmospheric Flight Mechanics Meeting, Austin, Texas, 11-14 August 2003.

11 Whalley, M., "A Piloted Simulation Investigation of a Helicopter Limit Avoidance System Using a Polynomial Neural Network", USAATCOM TR 97-A-004, NASA TM-1998-112220, January 1998.

12 Horn, J.F., Calise, A.C., Prasad, J.V.R, "Flight Envelope Cueing on a Tilt-Rotor Aircraft Using Neural Network Limit Prediction", Journal of the American Helicopter Society, Vol. 46, (1), January 2001.

13 Sahasrabudhe, V., Spaulding, R., Faynberg, A., Horn, J., Sahani, N., "Simulation Investigation of a Comprehensive Collective-Axis Tactile Cueing System," Proceedings of the American Helicopter Society 58th Annual Forum Proceedings, Montreal, Canada, June 11-13, 2002.

14 Yavrucuk, I., Prasad, J.V.R., Calise, A., "Adaptive Limit Detection and Avoidance for Carefree Maneuvering", American Institute of Aeronautics and Astronautics, Guidance and Navigation Conference, Montreal, Canada, August 6-9, 2001.

15 Einthoven, P., Miller, D., "The HACT Vertical Controller," Proceedings of the American Helicopter Society 58th Annual Forum Proceedings, Montreal, Canada, June 11-13, 2002.

16 Army Field Manual FM 1-203, Fundamentals Of Flight, 9 September 1983.

17 Gilson, R.D., Fenton, R.F., "Kinesthetic-Tactual Information Presentations – Inflight Studies," IEEE Transactions on Systems, Man, and Cybernetics, Vol. SMC-4, No. 9, pp.531-535.