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Boundary-Avoidance Tracking: A New Pilot Tracking Model

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Research concerning pilot-in-the-loop handling qualities has traditionally assumed that a pilot is focused upon maintaining a specific parameter, such as aircraft attitude or normal acceleration. This assumption has resulted in many important results and, by modeling this type of pilot behavior, a significant amount of predictive ability. In spite of these successes, many aspects of pilot control remain very difficult to predict. It is hypothesized that pilots often engage in a previously unrecognized type of tracking, boundary-avoidance tracking, where the goal is to avoid a hazardous parameter, such as ground impact, or a routine limit, such as an assigned minimum altitude. A variety of Simulink® models were built to study this phenomenon and it was found that treating the pilot gain as a function of the time to exceeding a given boundary can result in the type of control inputs typical of pilots in such situations, including the worst types of pilot-induced oscillations.

Nomenclature

K_{bm}	=	maximum boundary gain
t_b	=	time to boundary
t_{min}	=	minimum time to boundary with no boundary feedback
t_{max}	=	time to boundary when boundary feedback is the maximum boundary gain, K_{bm}
τ_b	=	time delay for boundary-avoidance feedback
x_b	=	displacement from boundary

I. Introduction

Pilot-in-the-loop flying qualities, also called handling qualities, have suffered a long drought of predictive ability. Many years of experience have produced guidelines for preventing most of the worst problems by creating specifications[1] to avoid known problems. In the end, though, only placing a pilot in a simulator or aircraft can answer the question, "How does this aircraft handle?" Regardless, some of the most hazardous flying qualities problems, such as pilot-induced oscillations (PIO), can appear without warning long after the aircraft is believed to be safe.[2]

The complexity of the human mind must rank as the most important reason among the very good reasons for problems in predicting aircraft handling qualities. Engineers have looked at pilot inputs and outputs and, from them, devised useful models for pilot behavior. These models have started with the assumption that a pilot attempting to control an aircraft is always attempting to maintain a given condition.[3] From this assumption—the 'point tracking' assumption—a variety of control strategies have been created attempting to predict the handling qualities produced with the human mind in the loop.[4]

The least predictable and worst instances of poor handling qualities—explosively unstable PIOs—have traditionally been explained by ascribing the oscillation to extraordinarily high pilot gains while the pilot is attempting to control a certain parameter. But these explanations did not correspond to the pilots' actual experience. The author has been learning, conducting, and teaching handling qualities flight tests for over a decade and has spent many hours discussing, with other pilots, the goings-on in the black box of the mind. While pilots spend most of their time maintaining a variety of parameters (point tracking), there are significant and routine moments of flight when maintenance of a parameter is of secondary interest to the pilot. It is during these moments that the point tracking assumption does not coincide with the experiences of the author and many other test pilots.

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The lack of correspondence between a pilot's experience in a hazardous PIO and the engineers' analysis of the same PIO led the author to consider what else the pilot might be tracking during these events. One particular anecdote was especially informative: an experienced test pilot described a hazardous PIO as a continuous attempt to survive by alternatively attempting to prevent ground impact and prevent a low altitude departure. It seemed that this pilot and other pilots involved in a hazardous PIO experienced their PIO as a succession of opposing events, each an attempt to avoid a hazardous condition. Pilots were tracking a hazard, expressible as a boundary, in an attempt to prevent a condition represented by that boundary. With opposing boundaries and the proper conditions, the resulting PIO might look no different than a PIO caused by high gain tracking of a single parameter but, because the actual focus of the pilot was incorrect, the traditional model of pilot tracking might be inadequate to describe or predict the situation. There is much anecdotal evidence that, at least in the case of hazardous PIOs, the point-tracking model is inadequate.

A series of studies and tests were conducted to examine boundary-avoidance tracking. First, Simulink® modeling was used to examine a variety of candidate schemes for boundary-avoidance tracking.[5] With a reasonable model scheme established, a variety of pilots were given a simulated tracking task and their control inputs were compared to the model.

II. Modeling Boundary-Avoidance Tracking

Simulink® was used to model a feedback control system. Initially, the system under control was a simple spring-mass-damper system but an aircraft model was later investigated, producing the same generalized results. The simplest reasonable model of human tracking, consisting of feeding back the rate with a gain and time delay, was used to simulate point tracking. Boundary-tracking feedback was added for each boundary and based upon a first-order prediction of the time to the boundary. A limit on feedback from both the point-tracking and boundary-tracking feedback loops was used to simulate the pilot's self-imposed limits and the feedback limits that would be imposed by an actual control system. A selector was developed because of the two types of feedback (rate and boundary), the pilot would only apply one at a time.[6] While the point-tracking feedback was limited to rate feedback, a variety of parameters for boundary-avoidance feedback were investigated. Figure 1 shows the simplified model.

While most of the initial effort was in the construction of the model, once the models were completed and tested many hours were occupied varying parameters and observing how the model behaved as each parameter was changed. There was no attempt to linearize the model because the nonlinearities were essential to describe the tracking behavior.

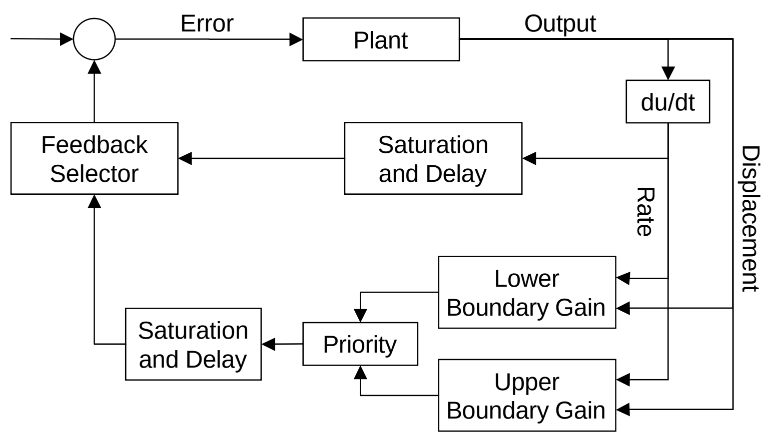

Figure 1. Study Model.

A. Boundary-Avoidance Feedback Algorithm

The most difficult problem was identifying the source of pilot gain during boundary tracking. Since the model used displacement boundaries, two main classes of feedback were immediately obvious—displacement from the boundary and time to the boundary. The second class was further divided into how the time to the boundary was calculated; either with instantaneous rate and displacement alone or with instantaneous acceleration added as well.

Displacement from the boundary produced unsatisfactory results because the rate of approach to the boundary was not considered. At close proximity to the boundary, the feedback was maximized regardless of relative rate. This model not only produced clearly unsatisfactory results, it was obviously not similar to a pilot's response to boundaries. A pilot's reaction at 10 feet above the ground when the descent rate is low is very different at the same height with a high descent rate.

Time to the boundary calculated from instantaneous displacement, rate, and acceleration was also unsatisfactory in this model. Acceleration could become high enough that boundary avoidance tracking would kick in even with the distance from the boundary rapidly increasing. In the 10-feet-above-ground situation, a pilot would experience an acceleration toward the ground while in a slight climb as a rapid slowing of the climb rate and would be more likely to respond directly to the condition of low or negative g than to the long-term effects of this unload. (Low or negative g may be a boundary in and of itself when unexpected or in close proximity to the ground.)

The most satisfactory results were produced when boundary-avoidance feedback was calculated as a function of time to the boundary using instantaneous displacement and rate. This methodology ensured that the only time a boundary was an issue was if there was a positive rate toward the boundary. There was also no boundary-avoidance feedback if the displacement was close to the boundary provided that there was very little rate toward the boundary. Both of these results correspond well with anecdotal evidence of pilot boundary-avoidance tracking. Table 1 describes the method used to determine boundary-avoidance feedback.

Table 1. Boundary-Avoidance Feedback Computation.

Situation	**Boundary Awareness**	**Boundary Feedback**
Displacement inside, moving from boundary	No threat	0
Displacement inside, moving toward boundary		
$t_b \geq t_{\min}$	No threat	0
$t_{\max} < t_b < t_{\min}$	Feedback increases linearly as t_b decreases	$\dfrac{t_{\min} - t_b}{t_{\min} - t_{\max}} K_{bm}$ (1) where $t_b = x_b \left(dx_b / dt \right)^{-1}$ (2)
$t_b \leq t_{\max}$	Maximum threat	K_{bm}
Displacement outside boundary	Maximum threat	K_{bm}

Two other problems were encountered during the creation of the model. First, there were occasionally times when all three types of feedback (point-tracking and boundary-avoidance for both boundaries) were non-zero. Second, when the displacement exceeded a boundary, the feedback was maximized but once the rate had reversed it was unclear what that feedback should do; return to zero because recovery to the other side of the boundary was imminent, remain maximized because the boundary was exceeded, or some combination of the two. When more than one feedback was non-zero, the highest signal was selected for feedback. Once again, anecdotal evidence was used to resolve this issue. Experienced pilots tended to react to the situation requiring the most attention if there were several issues imposing upon them. Indeed, the ability to prioritize tasks was an important element in evaluating a pilot. If the feedback gain was seen as the level of control effort required by the pilot for the task, then the amount of control effort for a particular task was a good indicator of its importance. In the case of the displacement exceeding a boundary, feedback was kept at a maximum as long as the displacement was outside the boundary. Using the analogy of an over-g, pilots will see any time above a g limit (the relevant boundary) as high risk, so their full attention will be placed to returning back to the normal g envelope.

B. Modeling Results

The following figures show the result of decreasing the displacement of the boundaries with an initial perturbation in the spring-mass-damper model. The rate-feedback point tracker gain was set to zero so the system response was limited to boundary tracking in this simple case. Boundary-tracking time delay (τ_b) is present so the boundary tracking feedback as depicted includes this time delay.

Figure 3 depicts the system response to the initial perturbation with no feedback

Figure 2 shows the response when symmetric boundaries are imposed and they are near enough for a single instance of boundary tracking feedback. While the second overshoot is larger than that of the first figure, it is not large enough to cause any response from the lower boundary tracker.

As the boundaries are moved closer, the second overshoot is sufficient to cause another instance of boundary-tracking feedback. But after that, the system continues open-loop. Figure 4 depicts this situation. A pilot would experience this situation as a 'bobble.' (Note that in this figure and the remaining figures in the set, the original boundaries in Fig. 2 are depicted by two short horizontal lines in the System Displacement.)

In Fig. 5, the boundaries are close enough that an oscillation is created. If the boundary trackers were not limited to a maximum feedback amount (K_{bm}), this would be an unstable oscillation.

Figure 5 shows the situation when the boundaries are close enough that the oscillation grows to exceed them. With the displacements moving outside the boundaries, the full gain is applied for a longer time, resulting in larger and larger overshoots. The size of these overshoots is limited by the maximum boundary-tracking gain but, if the boundaries were truly hazardous boundaries, the second overshoot might have ended the process altogether as the hazard was realized. Note the square-wave nature of the feedback, typical of the worst PIOs, and indicative of the boundary tracker holding the maximum feedback until the displacement is on the desired side of the boundary.

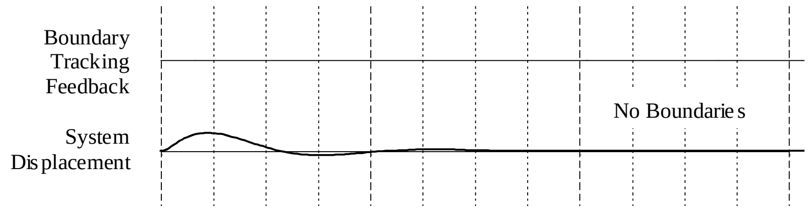

Figure 3. System Response With No Feedback.

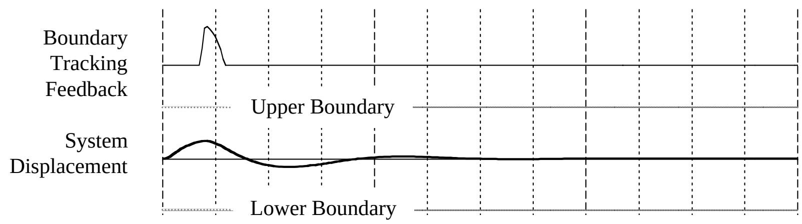

Figure 2. System Response with One Instance of Boundary-Avoidance Feedback.

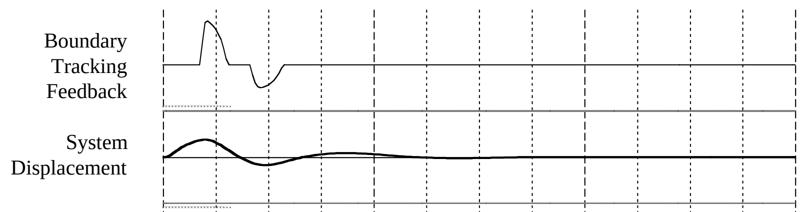

Figure 4. System Response with Two Instances of Boundary-Avoidance Feedback.

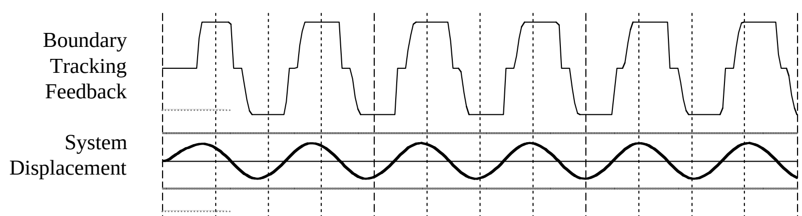

Figure 6. Boundary-Avoidance Oscillations.

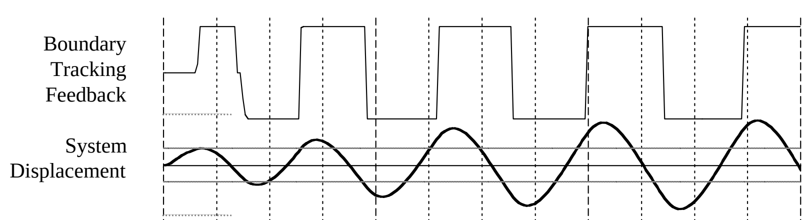

Figure 5. Unstable Boundary-Avoidance Oscillations.

Numerous patterns were noted while checking sensitivities to variations in the model.[7] Confirmation of these patterns through data analysis awaits further work.

1) Unstable boundary-avoidance oscillations grew ‘explosively’ until reaching the boundary tracker gain limits. This became more pronounced once excursions began exceeded the boundaries.
2) Feedback inputs for a boundary-avoidance oscillation that has diverged to K_{bm} were characterized by stop-to-stop inputs that strongly resemble the inputs made by pilots in actual PIOs.
3) Boundary-avoidance tracking produced extremely nonlinear (‘cliff-like’) results. Relatively small variations in K_{bm}, τ_b, t_{min}, or t_{max} in the boundary-tracking feedback loop marked the transition from a moderately damped boundary-avoidance response to rapidly divergent oscillations.
4) Increased boundary feedback delay (τ_b) could readily cause boundary-avoidance oscillations.
5) Unstable point-tracking oscillations can rapidly transition to catastrophic boundary-avoidance oscillations once boundary awareness is achieved. The transition may be marked by an explosive increase in feedback (inceptor) inputs.
6) Boundary-avoidance PIO can occur where point-tracking PIO was not present. A boundary-avoidance PIO could quickly arise from a disturbance large enough to assault one of the boundaries, provided the boundaries were sufficiently tight and/or the increase in gain brought by boundary-avoidance tracking was sufficiently greater than the gain for the point-tracking task,.
7) Experimentation suggested a wide range of types of boundary-avoidance tracking; from minor ‘hits’ necessary to remain within relatively unimportant limits to unmitigated full control inputs to prevent a crash.
8) The basic construction of the model resulted in some interesting characteristics that closely followed actual pilot tracking and experience with PIO:
   a) By saturating the feedback gains, unstable oscillations only grew until the saturation created a stable oscillation. These limit-cycle oscillations were very similar to some PIOs caused by pilots that were working with high effort yet limiting the size of their stick inputs for safety’s sake.
   b) If the boundaries were reduced to zero displacement, the oscillations and control inputs were very similar to those produced by pilots engaged in stop-to-stop oscillations.
9) In many conditions, especially with relatively short time delays and stable or well-damped systems, boundary-avoidance tracking was effective at preventing an excursion.

The boundary-avoidance tracking model produced results that seemed to coincide well with actual pilot tracking, especially compared to cases when boundaries presented a high risk to the pilot and aircraft. It is very important to keep in mind that, in almost all cases, tracking to avoid a boundary is a necessary part of a pilot’s survival toolkit. In many cases, the pilot’s response will be necessary and sufficient for survival but there may be times when this important survival tool becomes a significant hazard.

Pilots faced with a life-and-death boundary will apply whatever control input it might take to ensure survival. On the other hand most boundaries present little or no safety threat—often far less than an unmitigated control input—so pilots will limit their response to minimize the total risk. This range of reactions to a range of boundaries might be considered a spectrum of responses. This spectrum, illustrated in Fig. 7, shows how the consequence of a boundary excursion will affect the boundary tracking task and introduces the term “boundary-escape tracking.” Boundary-escape tracking is a limiting case of boundary-avoidance tracking where the threat represented by the boundary will drive the pilot to responses limited only by the mechanical characteristics of the pilot’s body and the aircraft inceptors. Conversations with pilots that have encountered stop-to-stop catastrophic PIO suggest that these can be explained as instances of boundary-escape tracking.

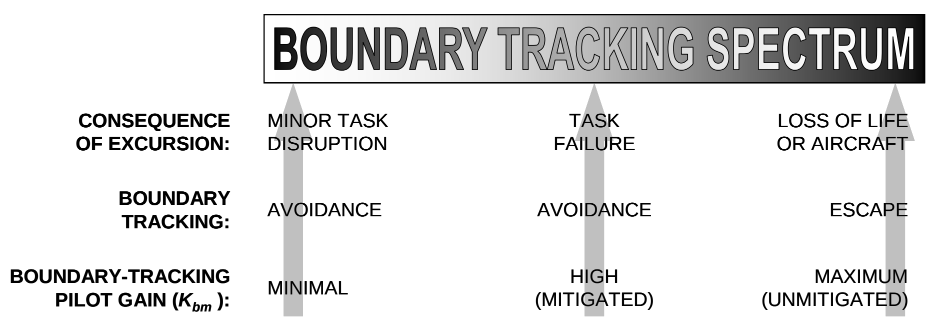

Figure 7. The Boundary Tracking Spectrum.

III. Simulator Evaluation

A simple tracking task was required for gathering pilot tracking data in relation to opposing boundaries. A tracking task designed around a North American Navion model created in Simulink® (and provided free-of-charge in the Aerosim Blockset by Unmanned Dynamics, LLC) was used.[8] A constantly changing altitude profile was created by recording the altitude changes of a simulated Navion with constantly changing small amplitude inputs. The pilot subjects were given a simple display showing only their altitude relative to the lead aircraft, with upper and lower boundaries presented for reference. Each of these three parameters—relative altitude, upper boundary, and lower boundary—were depicted by a horizontal line on a vertical scale. Aircraft roll and yaw were disconnected from the pilots' control stick and kept near zero using an autopilot. An autopilot was also employed to control the throttle setting to keep the airspeed close to the target's airspeed.

Pilots were given a series of tasks, starting with an orientation run of three minutes to familiarize them with the control and display setup. Each data run consisted of a continuous tracking task with steadily closing boundaries. The boundaries were initially set wide enough that they presented little threat, then each minute the boundaries were brought 25 percent closer than the previous displacement. Pilots were told that their primary goal was to remain clear of the boundaries as long as possible and the simulation was ended immediately upon an excursion. The lead aircraft motions were repeated every minute so that, aside from the displacement of the boundaries, the tracking task remained the same. Three data runs were taken with each pilot. The first consisted of the basic task with the simulated aircraft flown without modification. The second task added a 300-millisecond time lag to the pilot's inputs and the third, a 0.3 radian per second rate limit to the horizontal tail deflection. The subjects were told that each data run was different than the one before, but were not informed of the nature of the change.

Eight subjects were selected with the intent to sample a wide variety of backgrounds. Most of them were familiar with the concept of boundary-avoidance tracking but unfamiliar with the mathematical techniques for predicting boundary-avoidance inputs. Each subject spent about 30 minutes in the simulator; data was collected for all simulator runs and most subjects successfully completed each attempt. During the tasks pilots were encouraged to discuss their techniques, observations, and impressions. Numerous parameters were recorded and data was taken at 100 samples per second.

A. Simulator Data Reduction

A variety of data reduction techniques were attempted, including examining minute-by-minute power spectral densities of the pilots' inputs, but the most productive analysis was obtained by varying the four basic boundary tracking parameters (t_{min}, t_{max}, K_{bm}, and τ_b) until the predicted boundary tracking feedback most closely matched each pilot's inputs for instances when boundary-avoidance tracking was likely. Data was also analyzed to provide tracking performance results for comparison with boundary-avoidance parameters. All of the results presented come from the time domain.

B. Simulation Results

Overall tracking performance and subjects' comments validated the model as a reasonable representation of a formation pitch tracking task. The relationship between stick position (and, in this model, horizontal stabilizer position) and altitude involved a fair amount of lag, was not stable, and essentially acted as a pure integrator. The constant motion of the lead aircraft required constant pilot input, but the type of input heavily depended upon the operator. Some techniques were more effective than others. Figure 8 depicts the tracking performance of each subject. Subjects are arranged in rough order of experience, where the digit in the 'subject' label corresponds to their

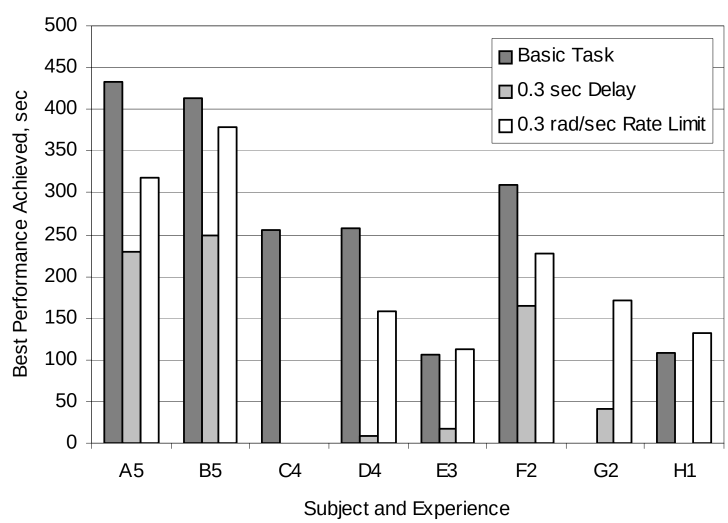

Figure 8. Overall Tracking Performance.

experience. A “5” labels the most experienced formation pilots—fighter pilots with thousands of hours—while a “1” labels the single subject that had no piloting experience outside a flight simulator. In between, “4” labels transport/bomber military pilots, “3” civilian pilots with little formation experience, and “2,” engineers with some “stick time” but no pilot qualifications.

Figure 8 indicates no surprises; experience certainly helps but, as in the case of subject F2, video game experience unsurprisingly prepared the subject for a task that felt more like a video game than flying. Most subjects found the rate limit less of an issue than the time delay, even noting that the task “seemed the same” until they encountered the rate limit and lost control. Some subjects quickly identified the time delay and all subjects immediately recognized that the task with the time delay was more difficult than their first run with the basic system.

Figure 9 shows the results for the longest data run accomplished, A5’s basic run. The top time history depicts the displacement and boundaries and the bottom time history depicts the pilot’s control inputs and the control inputs for the lead aircraft. For clarity, the lead aircraft control inputs are depicted at three times their actual value. This pilot succeeded in part because of self-imposed tight control deflections limits. Even in a short PIO (encountered at approximately 345 seconds) the subject kept the control inputs to less than half the maximum available elevator deflection of 0.26 radians.

The following figures depict a variety of predicted boundary-avoidance inputs compared with the pilot’s actual inputs. The predicted inputs were created by feeding the displacement and rate created by each pilot into the boundary-avoidance tracking model and plotting the predicted result with the pilot’s actual response. In order to compute the boundary-avoidance feedback, the boundary trackers required K_{bm}, τ_b, t_{min}, and t_{max} in addition to rate (dx_b/dt) and displacement (x_b). Boundary displacement was known but trial and error was used to find K_{bm}, τ_b, t_{min}, and t_{max}. These four parameters were varied until the best fit was achieved for hypothesized instances of boundary-avoidance tracking at the smallest achieved boundaries for each run. Most of the runs terminated with a PIO, so these final inputs were of particular importance for adjusting the parameters.

Each parameter controlled a specific part of the shape of the feedback. The delay shifted the curve in time but did not affect the shape. Increasing the maximum boundary gain stretched the response vertically but did not affect the start and stop time of the response. The time from the boundary for minimal non-zero gain, t_{min}, controlled the time span of the input and whether or not there was an input. Finally, the time from the boundary for maximum gain,

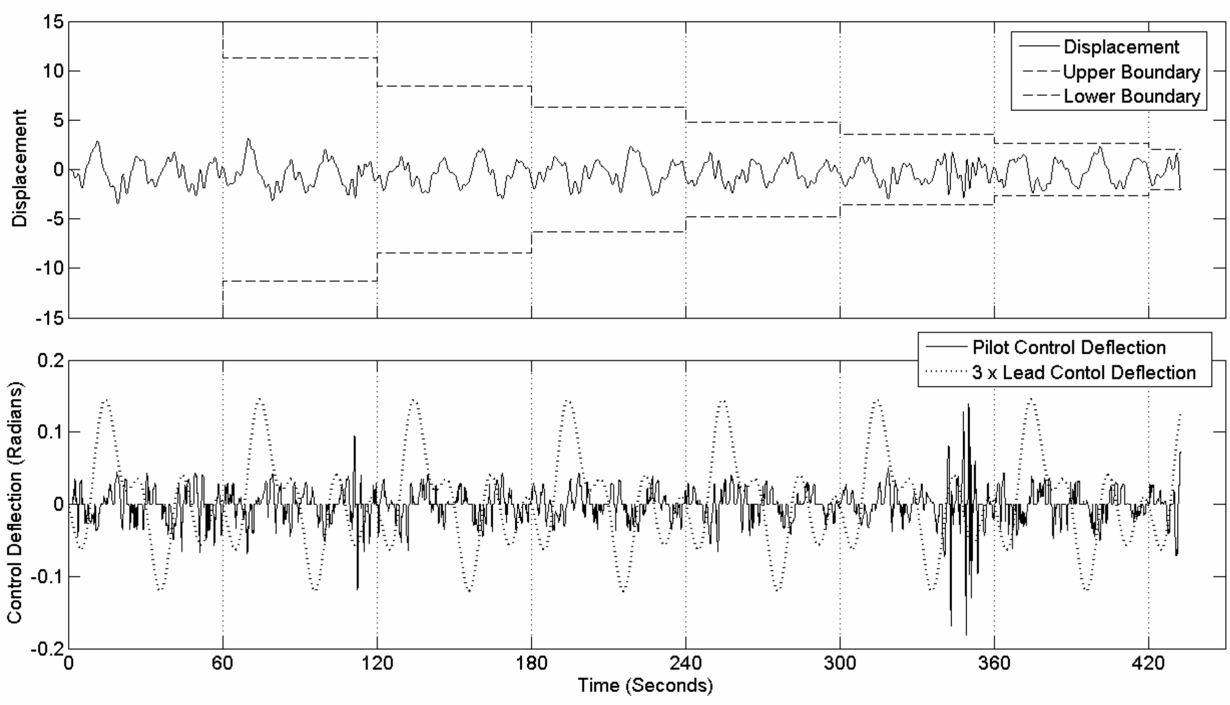

Figure 9. Sample Data Run.

t_{max}, controlled the height of the curve until the maximum gain was reached. If t_{max} was large enough that the maximum gain was reached, continuing to increase t_{max} steepened the input gradient until t_{max} equaled t_{min}, when the feedback became rectangular. If the boundary was set at zero the boundary-avoidance input would be a square wave switching between maximum positive and negative gain as the displacement passed the midpoint. Setting the parameters so the boundary feedback most closely matched the pilot response was a subjective task, but the constraints imposed by the theory limited the type of response curve that could be created. In the end, there was little room for variation in the parameters to provide a reasonable match.

1. Simulator Study, Case 1

Figure 10 presents the first example: the final ten seconds of the least experienced subject (H1) accomplishing the basic tracking task. The first three inputs were likely intended to control the excursion of the displacement and were made with the time-to-boundary (t_b) in excess of 2.1 seconds, so no boundary tracking was predicted. The third input, at 103 seconds, was held too long, so the displacement rapidly headed toward the lower boundary and the first boundary-avoidance input was begun just after 104 seconds. The remainder of the inputs were indicative of a boundary-escape PIO (rapid selection of the maximum inceptor displacement), with the second-to-last input sufficient to drive the system out of the lower boundary. There was an anomalous input at about 108.3 seconds, when H1 momentarily took out the input needed to minimize or prevent an excursion. In previous runs, H1 had occasionally moved the stick the wrong direction and may have momentarily misinterpreted the lack of sufficient response as an incorrect control input. If so, the subject recognized the true error and rapidly returned the stick to its maximum displacement, but too late.

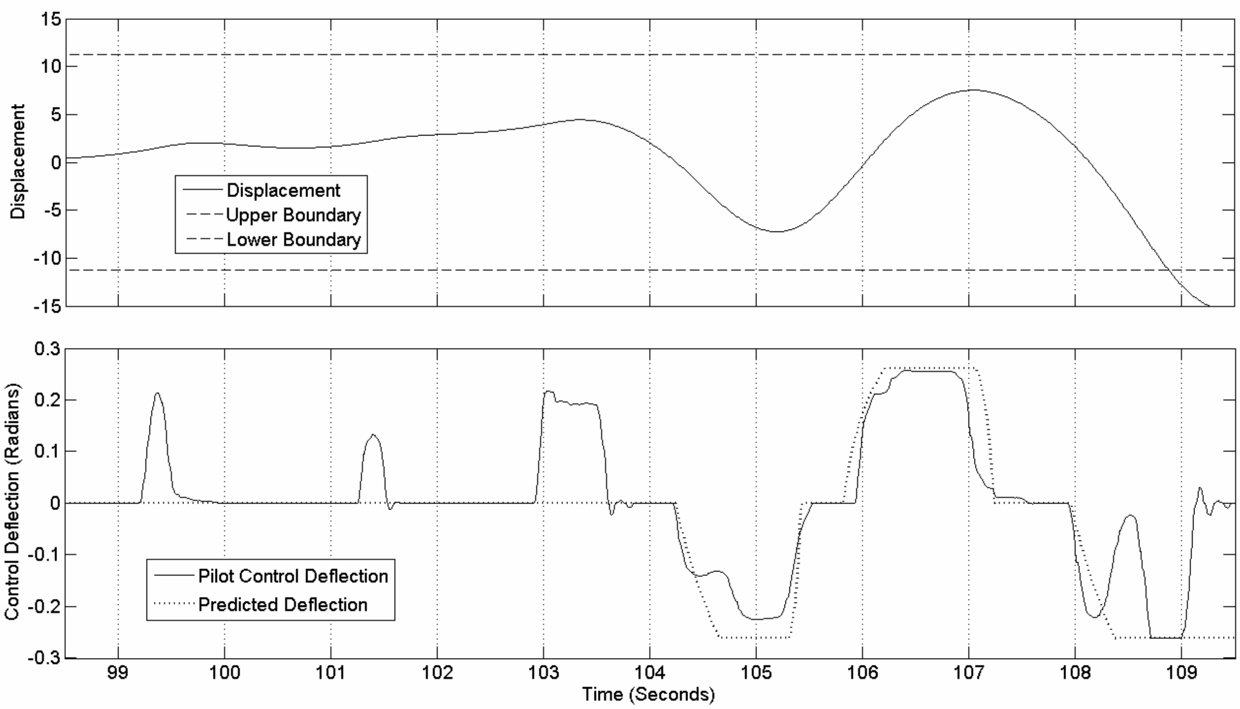

Figure 10. Boundary Tracking Correlation Case 1.

Subject H1, K_{bm}: 0.26 rad (max avail.), τ_b: 300 ms, t_{min}: 2.1 sec, t_{max}: 1 sec

At 109 seconds, when the displacement exceeded the lower boundary, the subject did not behave according to theory. Instead of maintaining full control deflection, the subject removed the input once the displacement exceeded the boundary. There are two possible reasons for this: first, the subject knew the task was over at that point, and second, with the rates decreasing and with an excursion a reality, the subject was beginning the process of attempting to stabilize inside the boundary. Both of these reasons exist, in part, because this was a task with no real risk and no need to continue. This was a trend for all subjects. None of the subjects maintained a full deflection input until the displacement was within the boundary. It seems likely that, for the case of boundary-avoidance tracking where the boundary did not represent a real risk to life and limb, once the task of remaining inside that boundary was failed, the pilot turned to the task of preventing another excursion out the other side. Additional study is required to see if this holds for the case of boundary-escape tracking, when being outside the boundary is a clear risk to life and limb.

2. Simulator Study, Case 2

Figure 11 shows the same subject, H1, in another PIO. This time, though, the PIO was successfully exited. The most important part of this example is the contrast between the excellent boundary-avoidance correlation with the two central inputs and the poor correlation with the bordering inputs. It was not possible to tune the boundary trackers to correlate with all four inputs. Pilots would often note that they were occasionally tracking specifically in relation to a boundary to prevent a boundary excursion. All other inputs were typically described as minimizing rate and keeping the displacement as near the center as possible. This example of short-term boundary-avoidance tracking may show this transition.

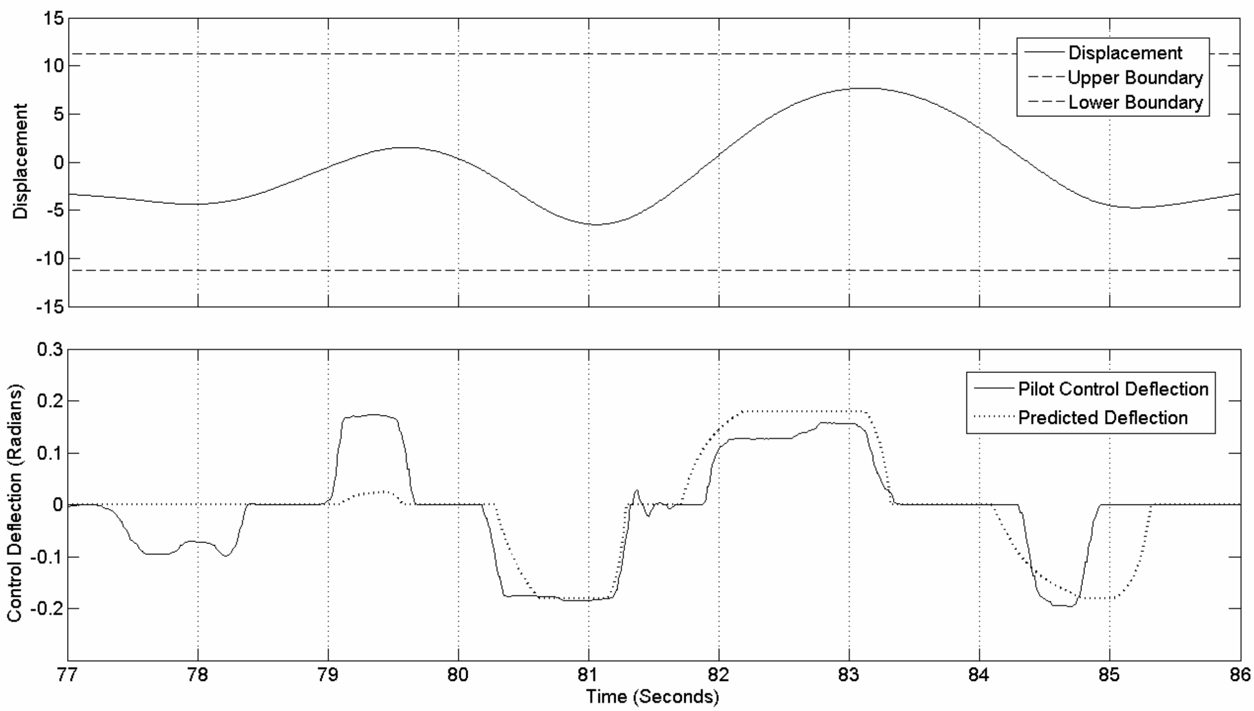

Figure 11. Boundary Tracking Correlation Case 2.

Subject H1, K_{bm}: 0.26 rad (max avail.), τ_b: 320 ms, t_{min}: 2.4 sec, t_{max}: 1.1 sec

3. Simulator Study, Case 3

The most interesting part of Fig 12. is the highly asymmetric oscillation encountered in the first 10 seconds. The asymmetric nature of this oscillation is driven in part by the motions of the lead aircraft, but the pilot's response is modeled nicely by the boundary-avoidance theory.

4. Simulator Study, Case 4

The final 20 seconds of an experienced fighter pilot's successful run is shown in Fig. 13. This subject carefully limited his stick motion to only a third of that available and employed a wide variety of techniques to manage such a strong performance. This figure illustrates how tuning the boundary-avoidance model could become problematic. In cases like this it became important to try to identify those inputs that were in response to a boundary then tune the model to those peaks. It may even be counterproductive to choose constant parameters for such a long time span since an experienced operator will constantly adjust the many things he's observing and the many variables in his response. The selection of parameter values for this time segment was exclusively based on the final PIO—the excellent correlation for the two peaks at about 400 seconds suggests that they were also responses to the boundary.

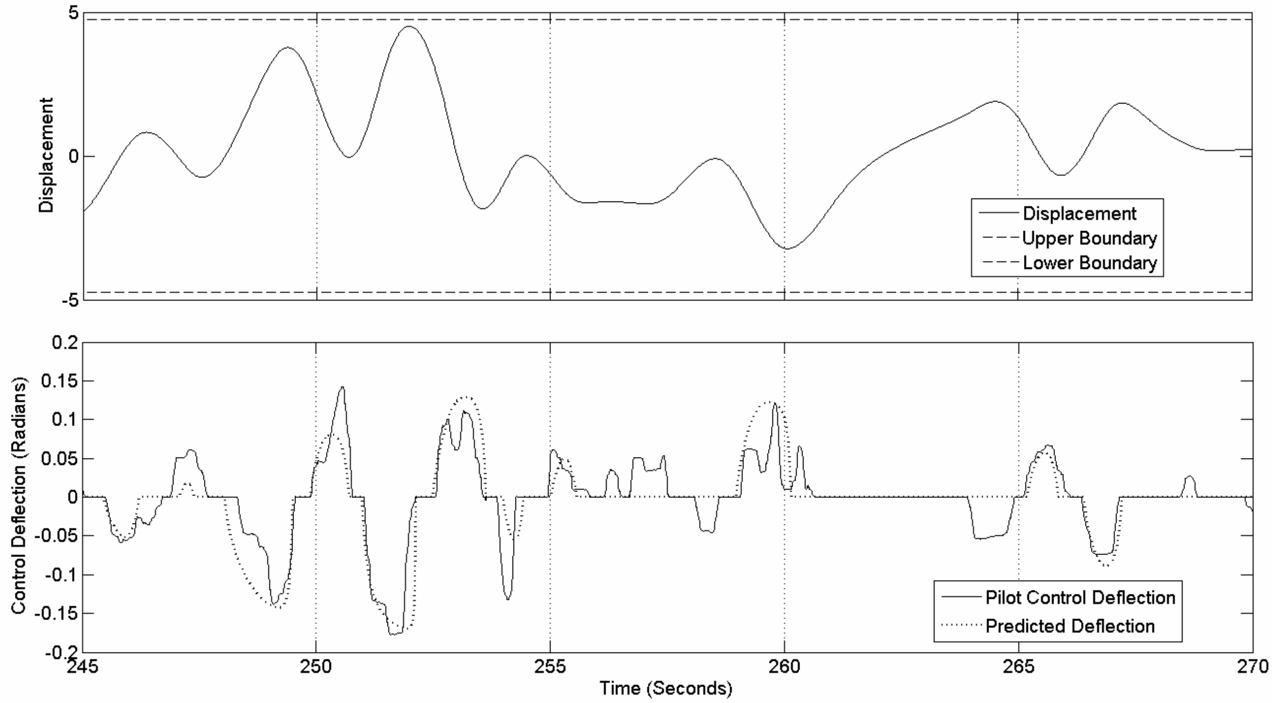

Figure 12. Boundary Tracking Correlation Case 3.
Subject F2, K_{bm}: 0.17 rad (65% of max avail.), τ_b: 150 ms, t_{min}: 2.5 sec, t_{max}: 0.2 sec

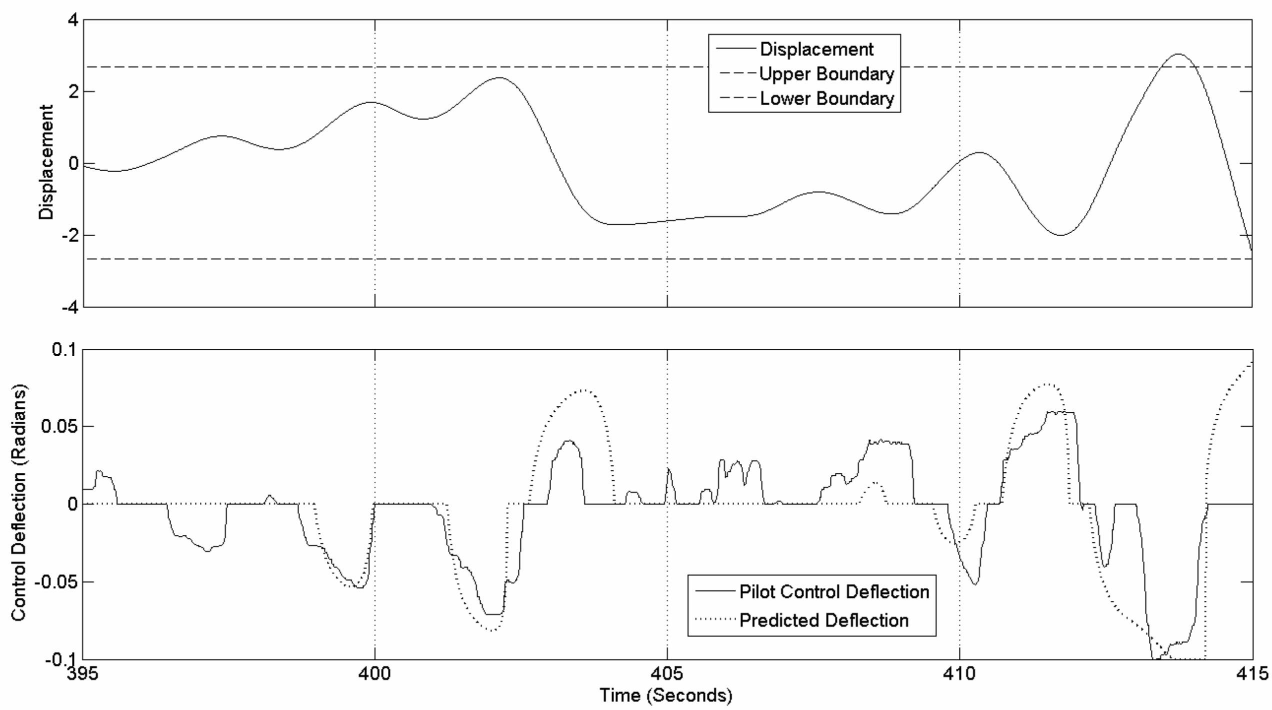

Figure 13. Boundary Tracking Correlation Case 4.
Subject B5, K_{bm}: 0.10 rad (38% of max avail.), τ_b: 170 ms, t_{min}: 2.4 sec, t_{max}: 0 sec

5. Boundary Tracking Parameters

In all, a total of 27 runs were successfully analyzed for boundary-avoidance tracking parameters. Parameters were found for smallest achieved boundaries, ranging from 15 distance units all the way down to the most successful tracking within boundaries of only two units. The four parameters; K_{bm}, τ_b, t_{min}, and t_{max}, were then compared to the tracking performance in an effort to find how these parameters affected the pilot's ability to remain within the boundaries.

Variation in the time-to-boundary parameters (t_{min} and t_{max}) showed little correlation with tracking success except for unusually high values of t_{min}. If the time-to-boundary for maximum gain (t_{max}) was one second or greater, tracking success was quite poor. For successful tracking, the values of t_{min} and t_{max} fell within a relatively narrow range; for runs with tracking times in excess of 60 seconds, the mean value for t_{min} was 2.8 seconds with a standard deviation of 0.5 second. For t_{max} the mean value was 0.3 second with a standard deviation of 0.2 second. In spite of the poor correlation between t_{min} and t_{max} and the tracking success, there was some correlation with the difference of the two values, where tracking success increased somewhat as t_{min} - t_{max} increased. Figure 14 depicts the time parameters found for all runs.

Maximum boundary gain correlated well with tracking performance. The more the subject was willing to displace the controls, the shorter the subject's tracking time tended to be. A combination of the time and gain parameters, hereafter called the 'boundary tracking parameter' (BTP) provided the most interesting results. BTP is simply the difference of t_{min} and t_{max} divided by K_{bm}. Figure 15 depicts the logarithm of the BTP against the tracking time for each run.

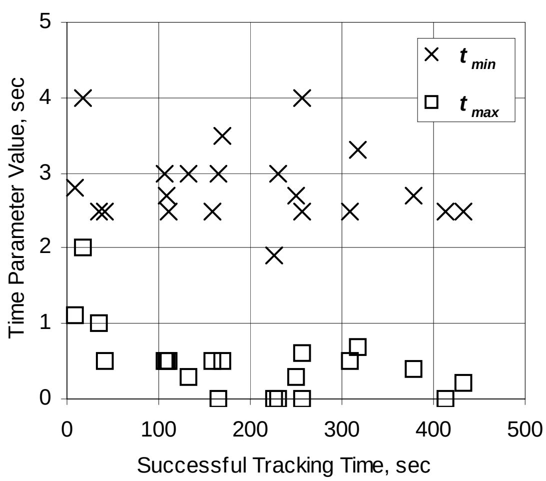

Figure 14. Effect of Boundary Tracking Time Parameters on Tracking Success.

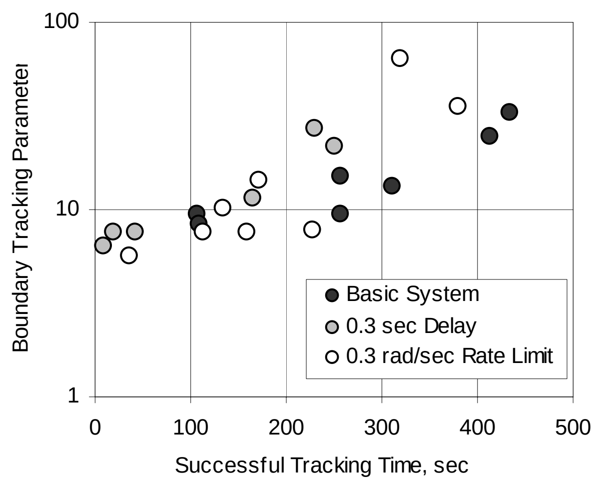

Figure 15. Boundary Tracking Parameter vs. Tracking Success.

These results confirm the intuition of pilots, especially pilots that fly high-performance aircraft in situations where the aircraft has much more control authority than necessary for the task at hand. When learning to fly formation, pilots are taught to minimize their control motions, react as soon as possible so their reaction can be minimized, and keep the controls still when possible so the natural aircraft stability can do the job. Some training criteria are defined in terms of limits; pilots are expected to remain within standardized criteria. But the best students rapidly intuit that over-attention to these boundaries can result in poorer performance than allowing the occasional excursion to keep their inputs under control. BTP parallels the aggressiveness of the pilot's inputs by considering the gain in the denominator and the slope of the pilot's inputs in the numerator. All other things being equal, reducing the difference between t_{min} and t_{max} decreases the amount of time it takes for the input to go from nil to the maximum gain, increasing the likelihood of overcontrolling.

IV. AREAS FOR FURTHER STUDY

Anecdotal evidence suggests that pilots respond to boundaries as a function of perceived risk; with risk being some combination of probability and consequence. Probability must take into account the pilot's perception of aircraft controllability. Pilot experience and skill would reduce the delays in recognizing the need for boundary-avoidance tracking and increase the accuracy of the risk assessment. An inexperienced pilot's response to a given situation would be unpredictable because the combination of low-reliability risk assessments, slow or inappropriate control inputs, and late recognition of the hazard would produce an extraordinarily wide variety of responses. New pilots in a simulator routinely demonstrate that there is a wide variety of ways to crash from the same initial conditions. They also almost always crash with the controls fully deflected, as would be expected as they attempt to avoid the rapidly approaching ground. In the near-term, modeling the pilot risk assessment may be an intractable task because there are just too many unknowns. It seems, though, that the risk of exceeding a boundary may be calculated with some accuracy by comparing the controllability of an aircraft with the control necessary to prevent exceeding the boundary. This model assumes a pilot with perfect knowledge of the situation but this limiting situation might still provide much useful information.

The results of this research into boundary-avoidance tracking suggest that it might provide a framework for increasing our understanding of how pilots control aircraft. It asks more questions than it answers, but it suggests many research opportunities. How do pilots perceive different types of boundaries and how do they perceive the risk of exceeding those boundaries? Of the historical PIOs for which there is data, is there a boundary-avoidance explanation and how do we learn from them to predict and prevent future similar events? Are there additional time delays added when a transition from one type of tracking to another is made? Are there instinctive responses that may trigger boundary-avoidance tracking?

V. CONCLUSIONS

Pilots attempting to closely control an aircraft do not just attempt to maintain a specific parameter. They also occasionally, and sometimes exclusively, control the aircraft in an attempt to avoid a specific parameter. This is called 'boundary-avoidance tracking' and, in addition to explaining some hazardous PIOs, this type of tracking might also increase analytical understanding of normal tracking tasks; tasks that often involve maintaining a desired condition within specific boundaries.

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