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Smart-Cue and Smart-Gain Concepts Development to Alleviate Loss of Control

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Unfavorable pilot–vehicle-system interactions including pilot-induced oscillations have long been an aviation safety problem. This was true 100 years ago when the Wright brothers first demonstrated powered flight, and it is still true today even for advanced fly-by-wire flight control systems. Although the effective aircraft dynamic properties involved in these events have been extensively studied and understood, similar scrutiny has not been paid to the many aspects of the primary manual control system that converts the pilot control inputs to motions of the control surfaces. It has often been tacitly assumed that the adoption of fly-by-wire systems has eliminated the primary manual control link as an important player in loss of control situations. Consequently, the impact of static and dynamic control system effects that distort ideal pilot-to-surface relationships, the near absence of manipulator tactile cues for some fly-by-wire systems, as well as the total elimination in fly-by-wire systems of some favorable cues present in traditional hydromechanical systems have not received detailed attention. The concept of dynamic distortion has significantly evolved in work conducted by Systems Technology, Inc. during a two-phase program sponsored by NASA Dryden Flight Research Center. In this work the "distortion" of interest results from control surface rate limiting and is quantified by the surface position error, whereas the "distortion metric" is the position lag. A force feedback cue (the constraining function) and/or a command path gain reduction are created when the position error exceeds the position lag (the alerting function). The smart-cue and smart-gain concepts, as described in this paper, are remarkable in their simplicity. The overall implementation does, however, require hardware in the form of a programmable, back-driven force feel system.

I. Introduction

BEFORE the Wright brothers, both aeronautical theorists and practical engineers focused on aircraft that were stable. This made sense because many of the experimental efforts used aircraft models that were not controlled and, hence, were intrinsically designed to be very stable. But these craft did not turn very well, and, as their stability was generally with respect to the air mass, they were quite sensitive to gusts. The Wrights changed this, with the realization that *controllable* flight, even at the price of aircraft stability, was essential. They reasoned, based at least in part on their experience with bicycles, that stability around desirable flight paths was indeed central but that the secret to this (stated in modern terms) was to have a *system* comprising the pilot–vehicle combination that was controllable and stable. Of course the Wrights' efforts worked out, but ever since there have been several generations of different problems in pilot–vehicle system control, some of which persist today, more than 100 years after the first powered flight. Unfavorable aircraft–pilot couplings, including pilot-induced oscillations (PIOs), have been particularly ubiquitous although not, by any means, the only variety.

At present, the aircraft flying qualities community has sufficient understanding of pilot–vehicle systems in general to make the case that some effective vehicle dynamics characteristics can be considered to be either ideal or good enough. Departures from these nominally ideal properties can then be defined as *distortions* that may underlie pilot–vehicle system problems. A common example is control surface rate limiting, where deviation from desirable values has been shown to lead to PIOs in some circumstances. Another example is misrigging of control system elements, such as mechanical maladjustments leading to control system backlash or excessive hysteresis. The common theme is that the actual manual flight control system is in some way deviating from an ideal system. The pilot is expecting one type of response, but the actual system is behaving differently because of the distortion. Within this general context Ralph A'Harrah of NASA Headquarters (now retired) proposed the Loss of Control Inhibition System (LOCIS)‡ wherein distortions are detected and appropriate cues are then introduced to the pilot by way of compensation. It was recognized at the time that this was still a general concept that had yet to be made concrete or specific. It served as a motivation for the work reported herein to attempt to quantify such conceptual terms as distortions and idealized systems as innovative and unifying principles underlying the development of corrective measures in the form of controller cues.

To advance this generalized theme concrete examples were needed. As part of a NASA phase II Small Business Innovation Research effort, Systems Technology, Inc. (STI) examined one critical distortion, that involving control surface rate limiting as a factor in category II PIO [1] and loss of control, and evolved and successfully demonstrated some conceivable alleviation means, herein referred to as the smart-cue and smart-gain. Because rate-limiting has been a contributing if not causal factor in all of the severe PIO loss of control events involving modern fly-by-wire (FBW) aircraft, this distortion remained the focus for the phase II flight-test program. This paper examines the dynamic distortion concept, and a companion paper examines the flight-test evaluation of the resulting loss of control alleviation schemes [2].

II. Background

The following sections discuss historical precedents regarding the use of cockpit inceptor cues, the underlying factors involving pilot–vehicle system loss of control, and existing mechanisms for eliminating unfavorable pilot–vehicle interactions.

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‡The A'Harrah LOCIS concept was recently awarded two U.S. Patents (#7,285,932 and #7,285,933).

A. Some Historical Precedents

For many years designers of manual primary control systems have used various devices attached to the cockpit controls to cue the pilot. In the simplest and most primitive systems the cockpit controls are mechanical, comprising cables, push–pull rods, etc., that connect the controls directly to the control surface. Thus, the pilot applies to the cockpit controls all the forces required to move and modulate the control surface. Here the controller cues reflect the aerodynamic forces on the surface. There may also be some acceleration-sensitive cues due to effective mass imbalances in the control system. These may be deliberate to provide a bob-weight effect that modifies the stick force$/g$ (where g is the gravitational constant), or inadvertent. In the latter instance they can sometimes be deleterious, for example, creating inappropriate stick forces during a catapult takeoff. Parasitic effects, such as cable friction, free play, etc., are minimized by rigging adjustments. Distortions are then the result of misrigging or maladjustments.

As speed regimes and size of the aircraft increased, the corresponding forces required by the pilot to move the surfaces also increased. To provide the pilot with some assistance, the cockpit controls were aided by various gearinglike devices, such as ratio changers or connecting the cockpit controls directly to a tab or servo tab that recruited aerodynamic forces to apply moments to the main control surfaces. Then came power-boost systems. Here the pilot retained a direct connection with the surfaces with the power boost operating in parallel to provide additional force.

The next stage in the evolution of manual control systems amounted to a watershed. In the 1940s Northrop Aircraft, Inc. developed a series of flying wing aircraft, starting with the N9M as a small experimental version and progressing to the large XB-35 and YB-49 bombers (which had wing spans identical to the Northrop B-2 that came along decades later). The early N9M experimental craft showed an alarming tendency for elevon hinge moment reversal at high angles of attack. This provided the motivation for the development of so-called fully powered surface actuation systems to completely separate the pilot from the control surfaces. This solved the basic problem intended and also introduced two very important side effects. The first was that the manual control system configuration inboard of the fully powered surface actuators made it somewhat easier to introduce small actuators as series links into the control path. This made possible the first stability augmentation systems (SAS) to correct some of the dynamic deficiencies in aircraft stability and control properties. By virtue of the series installation the pilot was unaware of the actions of the SAS, although the limited authority made it possible for the pilot to readily override any hardover SAS failures. (These were the days of single-thread SAS systems, and so such provisions were critical safety issues.) Because aircraft stability and control dynamic deficiencies were becoming rampant this, "side effect" of fully powered manual control systems was welcomed by flight control system designers charged with the development of SAS to remedy the dynamic deficiencies.

The second side effect was also of profound importance. With the isolation of the pilot came a loss of the proprioceptive and tactile cues associated with direct connection of the cockpit inceptors with their corresponding control surfaces. This created a requirement for the development of artificial feel devices to provide surrogates for the missing cues. It also created an opportunity for the introduction of other force and position cueing that had no direct parallel with those exhibited by conventional mechanical manual control systems. In essence, the newly required force producers could, in principle, feed back various appropriate dynamic variables as artificial feel system force cues. Then, when the pilot responded to these, the effective closed-loop pilot–vehicle system dynamics were improved just as with the SAS. Thus, the artificial feel system became a force stability augmentation system [3]. The difference between this and the conventional (motion) stability augmentors is that the latter are always available whereas the force stability augmentor requires the pilot to be active in the pilot–vehicle system loop to provide the stabilizing function. The similarity in the two categories of stability augmentation system is often overlooked and the awkward "force stability augmentor" phrase is simply not competitive with the easier "artificial feel system."

In the several generations of aircraft equipped with fully powered control systems, artificial feel to simulate the cues found in reversible mechanical systems has been introduced in a number of ways, some of which are listed in the following:

1) *Dynamic pressure* ($\bar{q}$) *bellows*: In longitudinal control systems on aircraft such as the Northrop flying wings and the Northrop F-89, $\bar{q}$ bellows provided a force proportional to dynamic pressure. The systems often used a dead center linkage to trim.

2) *Springs*: In lateral control systems springs were used to provide artificial feel. Preloaded springs were often used to help center the cockpit controller and to minimize hysteresis effects.

3) *Down spring*: In longitudinal control systems a preloaded spring that tended to push the stick down was used to modify the stick force per speed characteristic. Down springs were also used on reversible systems.

4) *Stick Pushers*: They were used to introduce controller forces proportional to Mach number to cope with the "tuck under" characteristic.

5) *Bobweights*: These are used to modify the stick force per the gravitational constant characteristic. Bobweights are sensitive to local acceleration, and so favorable locations were a critical design feature. They were most often located at or near the pilot location. They were often integrated with $\bar{q}$ bellows trim.

6) *Dual bobweights*: These were most commonly found on Grumman aircraft such as the F-14. They are designed to give an effective, favorable bobweight location and, with so-called "sprash pots," provide forces that are proportional to rate.

7) *Stick shakers*: This device was designed to mimic the natural tactile cue associated with the vibrations felt on a reversible stick as the aircraft approached stall. The device consists of an angle-of-attack detector that provided a vibration on the stick near stall.

Several of these devices were originally used in conventional, reversible manual control systems.

For FBW systems that employ force sensing sticks such as the General Dynamics Corporation (now Lockheed Martin Corporation) F-16, artificial feel system cues have been all but eliminated. Most FBW systems have, however, maintained position sensing control inceptors that feature significant range of motion. Some FBW systems such as that employed on the Boeing 777 restore artificial feel via a back-driven control column and yoke. Furthermore, the Lockheed Martin F-35 joint strike fighter features a fully programmable sidestick controller.

Command path gain reduction concepts are also not without precedent. Methods for mitigating PIOs on the space shuttle were investigated by NASA. Smith and Edwards [4] describe the PIO suppression (PIOS) filter that was designed to reduce pilot gain when potential for PIOs is high, while minimizing any additional phase lag. To achieve the desired gain reduction, the filter modifies the stick shaping function as a function of the amplitude and frequency of the pilot's input, thereby reducing the amount of rate limiting. In essence, the filter attenuates the pilot input at all frequencies. The PIOS filter was implemented in the shuttle control laws, and no pitch PIOs have been reported in the open literature since the 1977 ALT-5 event.

B. Fundamental Understanding: Key Underlying Factors

When means are considered to alleviate loss of control, there is a fundamental starting point in our current knowledge. That is, by virtue of having encountered, analyzed, and solved many pilot-associated loss of control situations in the past, there is an excellent understanding of many of the key factors involved. For example, for the very severe set of PIO problems the understanding of the key underlying factors is excellent. Essentially all PIO situations that have occurred in the past involve 1) the pilot as an essentially continuous controller element in a very high gain (e.g., unstable or neutrally stable) closed-loop pilot-vehicle system (PVS), and 2) fundamental mismatches between desired and actual effective aircraft characteristics.

In this dichotomy the pilot's characteristics have been largely unchanged through aviation's recent history, although they have been differentially affected by the evolving nature of the pilot's means of imposing control, that is, the evolving cockpit manipulators. The airplane-centered mismatches have tended to be era-sensitive.

In early era aircraft, directly connected pilot–surface primary control system PIOs were sometimes encountered due to aircraft stability and control deficiencies such as unstable short period and rapidly diverging spiral modes. They were very rare for stable aircraft with adequate flying qualities, although nonlinearities and misrigging phenomena very occasionally led to PIO problems.

In larger early aircraft that required some clever mechanical gearings (such as geared or servo tabs) to convert pilot-generated control forces to levels adequate for the movement of large control surfaces, the lags introduced between the pilot's direct control of a tab and the actual surface movement could significantly change the effective vehicle lags. PIOs were then quite often exhibited in high precision tasks such as tightly controlled approach and landing. Pilots were able, with substantial training and experience, to compensate for these essentially linear system lags.

When the first fully powered hydraulic actuating systems were introduced (e.g., on the Northrop flying wings and Northrop F-89, as well as somewhat later on the North American F-86 and similar fighters) the developmental problems of the surface actuators themselves played important roles. The most notable were associated with achieving a sufficiently high maximum surface rate, a high degree of effective linearity between pilot command and surface response, and aircraft dynamic sensitivities that did not require extremely careful pilot adjustment and variation of his gain while engaged in tight closed-loop tasks. The notable lessons learned during this period were associated with the following:

1) Extreme sensitivity especially when associated with rapidly varying aircraft gain. An important example was the Northrop XP-89, where in a dive from, say, $M = 0.8$, with a stick force/g near 70 lbs/g, the aircraft was converted to $M = 0.76$, with a stick force/g near 4–5 lbs/g that required a bobweight to reach those values from 3 lbs/g. After learning to cope with these changes, and occasional momentary PIOs, the airplane was considered "sensitive" and went on to an operational career of over two decades.

2) Sluggish actuation system dynamics and extreme maneuvers. The far-famed "JC Maneuver," a name coined by the upset test pilot of an early North American F-86, was an example of some of the first sustained and very exciting PIOs.

3) Insufficient maximum control surface rates. Most control system designers of early fighters experimented extensively, searching for minimum "magic" values of control surface rate that always insured adequate and precise control. Minimum surface rate has an important impact on the hydraulic system power supply requirements and, hence, aircraft weight. Only under somewhat unusual circumstances did actual aircraft have to put up with insufficiencies. A notable example resulted in the North American X-15 PIOs [5].

These encounters and experiences equipped designers with practical data and considerations to avoid these particular causes in most, if not all, of the later, so-called, century series fighters. The primary control systems still had direct connections from the pilot to the hydraulic valves directly controlling the surfaces, with appropriate intermediaries such as force producers, preloads for centering and reduction of hysteresis, etc., to achieve a sufficient degree of system quasilinearity.

Then came the modern era of FBW, with the ideal being a complete lack of mechanical connection between the pilot and the surface actuation systems. With all the nasty mechanical system nonlinearities and aircraft sensitivity variations potentially eliminated, what could possibly go wrong?

With FBW the pilot's manipulator can be a sidestick, and the control signals could be either force or displacement depending on the stick travels allowed by the detailed design. The earliest systems were basically force sticks, and a number of PIOs inevitably followed; more can be confidently expected in the future. With force sticks the following can be expected:

1) Cues related to trim state and actual surface position provided to the pilot from the stick forces and displacement are absent (i.e., the manipulator has lost its proprioceptive feedback display function).

2) There is no stick force indication of control surface rate limiting or even when the surface is on its stops. The mechanical forces imposed on the pilot are a gradient, and a major force buildup when encountering the stick stops.

3) Determining and adjusting the sensitivity range can be a very time consuming and expensive matter. For example, appendix C of [6] investigated 19 configurations with 34 pilots to arrive at compromises for the General Dynamics F-16.

On FBW transport aircraft there is currently a major philosophical difference in manipulator design. Airbus uses sidestick controllers, whereas Boeing uses back-driven wheel/columns. With the back-driven installations many of the cues removed by virtue of the mechanical design of sidesticks can be reinserted. Because the control wheel/columns are coupled and moving, again acting as a proprioceptive display, trim state, pilot–copilot interaction and joint situation awareness are also brought back to an earlier era.

C. Mechanisms for Eliminating Unfavorable Pilot–Vehicle Interactions

To quote the late John Gibson, a leading flying qualities engineer from the United Kingdom, the best way to eliminate unfavorable pilot–vehicle interactions is "by design." As described previously, the causes of unfavorable pilot–vehicle interactions are well understood. Thus, this knowledge base of analysis techniques and criteria must be applied throughout the design process. Note, however, that the application of criteria to provide a simple "black box" go/no go answer is a dangerous practice. The next mechanism to eliminate unfavorable pilot–vehicle interactions is flight test. To successfully uncover potential "handling qualities cliffs" appropriate evaluation tasks that force the pilot to interact with the aircraft in a closed-loop, high-gain manner are required. Example tasks include precision offset landings, aerial refueling, etc.

The last line of defense against unfavorable pilot–vehicle interactions are onboard systems that include PIO suppression filters, rate-limiting phase compensators, and various detection schemes/warning devices currently under development. PIO suppression filters such as those used on the space shuttle [4] modify the stick shaping function as a function of command amplitude and frequency of the pilot's input, thereby reducing the amount of rate limiting. Rate-limiting phase compensation schemes such as those employed on the SAAB Grippen [7] and the Boeing F/A-18 E/F [8] attempt to minimize the added phase lag associated with rate limiting by reversing the actuator when the commanded rate is of the opposite sign. These schemes appear to work reasonably well, although the handling qualities of the aircraft are often degraded although the alleviation schemes are active. Furthermore, there is no feedback cue to the pilot. Various onboard PIO detection schemes are also under development. These include a neural net-based technique developed by Accurate Automation Corporation [9], the real-time oscillation verifier (ROVER) concept of Hoh Aeronautics, Inc. [10], and STI's own wavelet-based loss of control analysis tool set [11]. The objective of these detection schemes is to provide ample warning to the pilot of impending PIOs or loss of control. Because the schemes designed to detect the oscillatory nature of PIOs need at least some fraction of the initial PIO cycles to positively detect the condition, ample warning may not be possible. That is, there does not appear to be a prePIO condition to detect.

Note that these "fix-it" approaches presume that the control system elements work as intended by the designer. Yet departures from the design ideals, ranging from inadequate surface rates or misrigging of control system elements to faulty design (ignorance or execution) are often root causes of unfavorable pilot–vehicle characteristics. The recognition that this can be the case in practice was one of the factors leading to the LOCIS concept of A'Harrah that inspired some of the activities of this program. This, in turn, leads to a somewhat more general view that "dynamic distortions" that result in the departures of the actual system from the ideal can be key factors. This is explored next.

III. Concept of Dynamic Distortion

Dynamic distortion, as defined herein, is characterized by a departure of the actual primary manual control system from an idealized system. This requires consideration of potential "ideal system characteristics" and the varieties of potential "distortions." Because this program is focusing on manual control system departures from the ideal, it becomes essential to review the sources and nature of those departures. These are somewhat different for classical hydromechanical and FBW systems. In classical manual control system departures from ideal system properties, referred to here generally as "static or dynamic mismatch from the ideal," can be classified in terms of their fundamental dynamic effects. The impact of these unfavorable properties on the stability of the PVS can be assessed by their describing functions [12]. A cross section of relevant inverse describing functions is given in Fig. 1.

Graded in terms of their deleterious consequences these would include:

1) *Introduction of unwanted thresholds and hysteresis* (e.g., from uncompensated wear at joints, increased friction, mismatched preload/friction adjustments, etc.): There is always some threshold and/or hysteresis in a mechanical system. The "ideal" here is simply to maintain it within viable bounds. The describing function for threshold is an amplitude ratio increase with the size of the input (see pp. 109 of [12]). This approaches the amplitude ratio of the linear system as the input size increases. Hysteresis (see Fig. 1) contributes both a phase lag and an amplitude ratio decrease. Considerable efforts are often taken in primary control systems to convert hysteresis to threshold via preloads, detents, etc.

2) *Introduction of backlash* (e.g., free play, inappropriately preloaded joints, and/or gearing): Because of its extremely deleterious dynamic properties (i.e., describing function characteristic combines increased amplitude ratio with increased phase lag) "backlash" per se is never acceptable in a manual control system. When present, it is always rigged out with preload and converted to at least a hysteresis and ideally to a threshold property.

3) *Deteriorated effector dynamics* (e.g., reduced effector bandwidth resulting from system pressure reduction due to partial loss of power sources or overloaded conditions, contaminated hydraulic oil and other flow discrepancies including loss of fluid effects): This refers, for example, to reduced effector bandwidth resulting from system pressure reduction due to partial loss of power sources or overloaded conditions, contaminated hydraulic oil, and other flow discrepancies including loss of fluid effects.

4) *Inoperable or jammed effector*: This includes servo valve jam, foreign object jamming primary control chain, fluid loss, etc.

Many of the sources of distortion, including their corrective techniques, are reflected in the much simplified Fig. 2. Some are fundamentally parasitic, such as control system and hydraulic valve friction and any backlash or free play in joints. Others are the consequence of design, such as flow rate limiting and valve bottoming. Others are corrective procedures, such as preloads to load out backlash or to counter the effects of friction. Recall that the actual distortions are not the specific sources themselves but rather the residual effect left from inadequate or imprecise compensation. The impact of these unfavorable properties on the stability of the PVS can be assessed by their describing functions [12].

In a modern FBW system several of these effects no longer apply. Indeed, their elimination as a source of primary control system problems in rigging and maintenance has long been one of the major practical arguments for FBW systems (e.g., Boeing 757 and 767 spoiler systems) rather than some of the more esoteric and academic justifications. Unfortunately, FBW mechanizations have introduced new static and dynamic mismatch sources. Some notable examples include 1) manipulator mismatches (e.g., between pilot and copilot for those systems without coupled, back-driven manual controllers), 2) mismatches between segments of mechanically uncoupled surfaces (e.g., flap, spoiler, or elevon segments), and 3) inadvertent or premature changes in system dynamics (e.g., primary control system gain changes intended to be functions of aircraft configuration actually introduced when the configuration change is commanded rather than when it is executed). A notable example of a "premature" change is a longitudinal system gain change that coincides with the pilot's movement of a flap system manipulator rather than when the flaps actually achieve the commanded position. Similarly, an example of an "inadvertent" change has occurred in the same flap system when a mismatch between flap segments occurred via asymmetric gust loading in the course of flap deflections, thereby locking the flaps in an intermediate position (as intended in the control system to avoid a serious asymmetric flap situation). But, the actual flap position was arbitrarily determined by when the gust hit

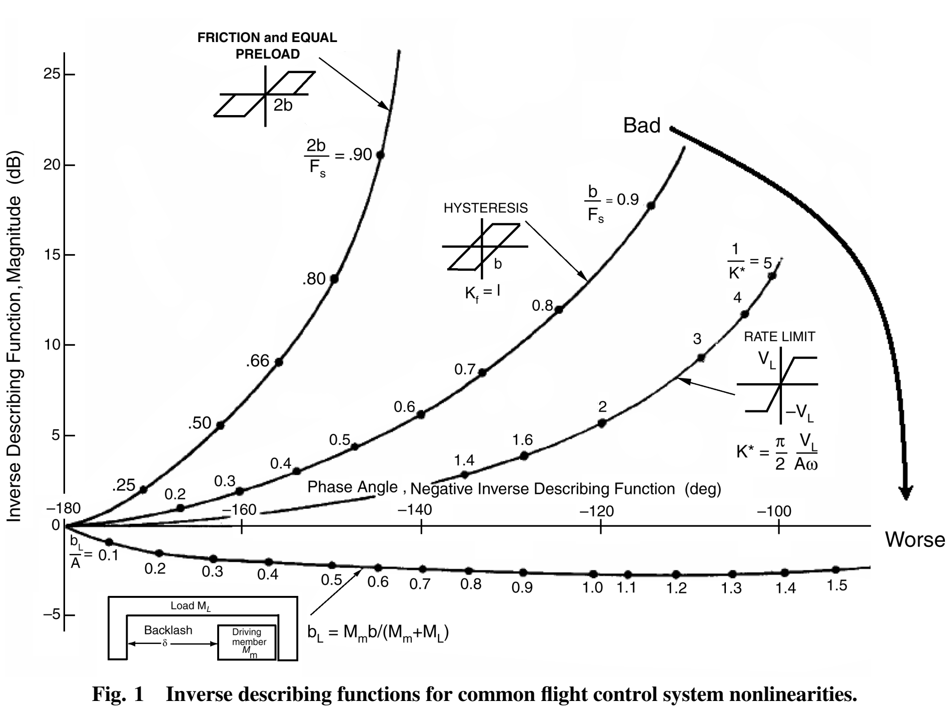

Fig. 1 Inverse describing functions for common flight control system nonlinearities.

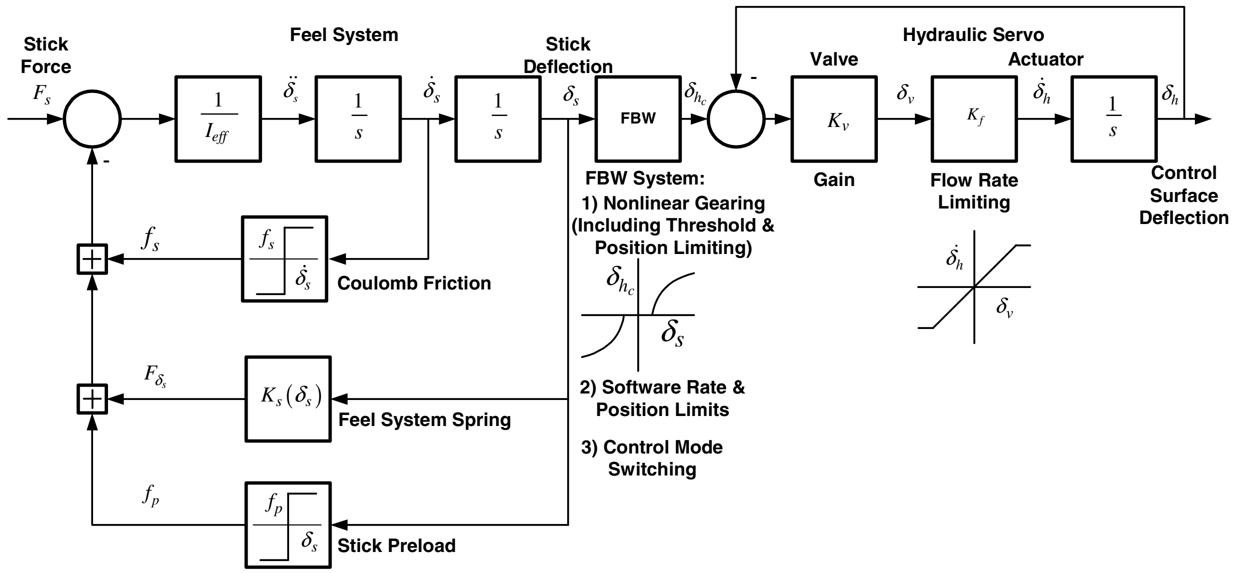

Fig. 2 Common manual control system nonlinearities.

rather than any preconceived situations, with the consequence that the primary control system gain was quite inappropriate for the actual effective aircraft dynamics.

The flight control system characteristic that will be the focus of the investigation herein is control surface rate limiting. Rate limiting plays a significant role in producing dynamic distortion in both classical and modern fly-by-wire flight control systems. In fact, rate limiting has been present in almost every severe PIO that has occurred with operational and flight-test aircraft since the North American X-15 event in 1959 [1].

IV. Idealized Manual Control System Paradigm

This section defines an ideal control system paradigm from which deviations from this ideal can be identified and measured.

A. Simplified "Ideal Linear System"

To provide a concrete example of what ideal system characteristics might be, consider the cases of pitch and roll attitude control. The nature of ideal effective vehicle plus manual control linear system dynamics for these cases for high-performance aircraft is well understood. In both cases, a simplified version of the desirable effective vehicle (aircraft + stability augmentation+ manual controller) pitch or roll attitude properties can be approximated over the frequency range of pilot control by

$$Y_{c_{\text{effective}}} \approx \frac{K_c e^{-j\omega\tau}}{j\omega}$$

Here τ is an effective time delay that provides a low-frequency approximation to all the high-frequency effective vehicles plus pilot dynamics and K_c is the effective controlled-element gain in the region of the pilot–vehicle system crossover. In terms of this linear system ideal the dynamic distortions will be of two varieties. The first would be essentially linear and, thus, can be directly reflected in incremental changes from the ideal τ or K_c. For example, distortions in hydraulic system pressure or flow rate that change the bandwidth of the surface actuators will cause a change in the actual τ. Inappropriate vehicle state compensation in the stability augmentation or artificial feel systems will be reflected in off-nominal changes in K_c, as would premature gain changes in general. The second variety of distortions are nonlinear in character and would include such items as rate limiting, the parasitic nonlinearities system friction, hysteresis, etc., and the introduced features such as preloads, detents, etc., deliberately inserted in the system to minimize the effects of the parasitic characteristics. For the second variety, the ideal linear system would be elaborated to include the net nonlinear effects of the unavoidable parasitic elements as countered by the deliberately introduced counters. The dynamic distortions would then reflect primarily the physical mismatches due to misrigging of the several preloads, detents, etc. Also, an elaborated ideal system will be developed next to reflect rate limiting that coincides with a virtual "valve-bottoming" feature.

In general, there are very few relevant quantitative data on the vast majority of dynamic distortion quantities. A notable exception is rate limiting, especially rate limiting as a factor underlying PIOs.

B. Nonlinear System Description

To give some perspective to the approach of this work to define an ideal manual control system, first return to the "ancient" history of fully powered surface actuation systems. As noted previously, the main stream began in the 1940s at Northrop Aircraft, Inc., when requirements for an irreversible, power-enhancing, surface actuation system became apparent from flight tests on early Northrop flying wings. The power-enhancement requirement stemmed from the very size and speed of such aircraft as the Northrop XB-35 and YB-49 bombers. In principle this could have been accommodated in other ways, such as power-boost, servo tabs, etc. However, the need for the irreversible feature was central because the hinge moment gradients reversed at high angles of attack, thereby presenting the pilot with very difficult if not impossible handling and control problems. A fully powered (in contrast to power-boosted) surface actuator assures the complete separation of the pilot from the forces associated with the control surface. The development of successful fully powered systems was probably the most important and long-lasting accomplishment in primary manual control systems in the two decades from about 1942 to 1962 when almost all high-performance aircraft were so equipped. Although fully powered systems are now ubiquitous, their perfection was a major achievement that required many exceptional engineering and technical breakthroughs. Major problems in mechanical and hydraulic system design, actuator system stability, and flying qualities, many at the margins of the then state of the art, had to be surmounted. Ultimately the systems became technologically mature and operationally effective and have since served several generations of high-performance aircraft. Still, fully powered manual hydro-mechanical primary control systems are not perfect, but an understanding of the nature of both their favorable and unfavorable features suggests concepts that can lead to more ideal systems in today's FBW or fly-by-light technology.

C. Potential Ideal System Paradigm

Figure 3 shows an idealized version of a single channel of a fully powered system typical of the end of the initial era in these developments. These are exemplified on such aircraft as the Northrop F-89D interceptor that served operationally for over two decades starting about 1954. In this system the pilot's manipulator (stick, control column, or pedals), restrained by an artificial feel system, is mechanically connected to a hydraulic servo valve via a combination of push–pull rods, cables, etc. The valve housing is integral with a hydraulic cylinder. A pilot command input, x_i, which moves the valve from its neutral position, creates an actuator system error ($x_e = x_i - x_s$) that ports hydraulic fluid to the cylinder. The valve-cylinder flow pathway(s) are arranged so that the cylinder housing x_s moves to reduce the valve displacement from neutral, thereby driving the actuator system error to zero. In the integral valve-cylinder configuration shown, the lags within the closed-loop actuator system are absolute minimums as the position feedback is inherent in the physical arrangement. The ultimately evolved successful versions are high-bandwidth actuators that add only a small lag and very light valve friction forces to the hydromechanical control chain. As a consequence, the evolved systems have minimum to no impact on the dynamics of the overall pilot–vehicle closed system in even the most extreme conditions of pilot control.

Such systems exhibit: 1) sufficiently high maximum surface rates, 2) minimum effective actuation system lags inserted into the manual control system (by virtue of high-bandwidth actuation system dynamics), and 3) a high degree of effective linearity between the pilot command and the control surface deflection.

For those aircraft where all of these conditions were satisfied, there appear to be no unfavorable pilot–vehicle interactions (e.g., PIOs) present in the flight record. It is for this reason that the actuation system illustrated in Fig. 3 embodies potentially ideal paradigms useful for the current work. There were, of course, many PIO events leading to the preceding assertion. These encounters and the technical advances leading to their subsequent correction were steps along the way to the technologically mature actuation systems that provide the essential features listed.

Unfavorable PVS interactions, such as PIOs, appeared to become more common as high-performance aircraft advanced into the FBW era. Whether this apparent increase was actual or just an artifact of closer attention or more extensive sensitivity to what are always unusual events is not at issue here. Suffice to say that essentially every new high-performance aircraft equipped with a FBW flight control system has exhibited PIOs at one time or another. These were, typically, linked to specific causes, most often associated with actuator rate limiting or excessive PVS lags. The contributing features have, in the main, been corrected for each specific aircraft after the appearance of the unfavorable events. In the process of dealing with the PIO specifics of many different aircraft, some specialists with a historical bent looked back to earlier days when, for some reason or other, the aircraft systems seemed to have been essentially PIO free. Thus, the justification for the return to the past in proposing the Fig. 3 system is to rediscover some potentially ideal properties. Just what these might be stems from looking at the differences between it and the more advanced FBW systems that have not been initially PIO free.

D. Differences Between Modern and Classic Manual Control Systems

The most profound difference between the manual control channels of modern FBW systems and that depicted in Fig. 3 is the replacement of all the mechanical features up to and including the servo valve with electrohydraulic and or electromechanical components. This replacement has many beneficial effects. Major differences between FBW and the idealized control system include 1) elimination of parasitic nonlinear features due to mechanical elements such as frictions, hysteresis, backlash, etc., 2) consequent elimination of the mechanical contrivances deliberately introduced to counter the unfavorable parasitic nonlinearities (e.g., preloads to provide stick centering in the presence of distributed cable system friction or to modify backlash to a hysteresis effect), 3) possible use of an essentially nonmovable manipulator for mechanical sticks or columns (as on the General Dynamics F-16), and 4) possible use of moving manipulators with prescribed back-drive characteristics (as with the Boeing 777).

Another somewhat more subtle difference occurs for circumstances where the pilot's command inputs are large and very rapid, as typically is present in a so-called category II PIO where rate limiting is a central feature in the PIO [13]. In the Fig. 3 "old" system, rate limiting coincides with valve bottoming and a consequent cue to the pilot that the controls are against a solid, albeit moving, stop. In these conditions the control surface is essentially directly connected with the pilot, and the valve is bottomed and the pilot command and surface travels are intrinsically locked together. Thus, the surface position can never lag the pilot command by more than the surface travel equivalent of the maximum valve travel from neutral. In modern FBW systems the pilot is not mechanically connected to the actuation system, and so such direct cues and intrinsic restraints are not present. It is these differences that offered some key insights and opportunities that have been explored further in this program.

E. Time Lag and Position Lag

In a large-amplitude rate-limited oscillation with the ideal system of Fig. 3, the surface and pilot's positional commands, as noted previously, are intrinsically linked between the fixed constraints provided by the stops defining the maximum valve displacements from neutral. The pilot's input essentially drives the valve back and forth from one stop to the other. In the course of such an oscillation the surface motion is going at maximum velocity (rate limit) after

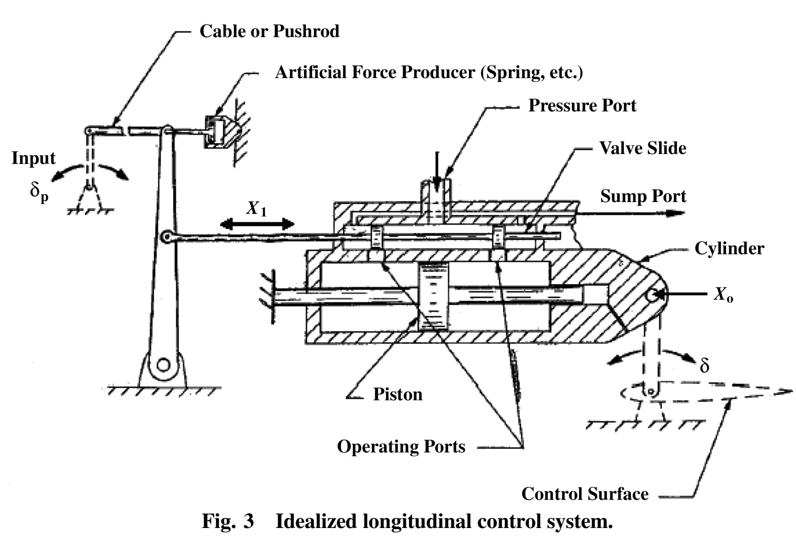

Fig. 3 Idealized longitudinal control system.

each input reversal. Consequently, the command input and the surface position are both essentially triangular waveforms, as idealized in the Fig. 4 traces. In this situation the two displacements are separated by a time delay equal approximately to the maximum valve displacement from neutral divided by the actuator rate limit. In aircraft manual control system parlance this quantity is called the *time lag* T_{lag}. This is a nonlinear system characteristic that is in no way to be confused with the more conventional effective time delay that defines the linear system properties of the hydraulic actuator closed-loop system.

The commanded and actual surface positions under these conditions are also tightly constrained. This is measured by the *position lag*. When expressed in terms of the surface position this is denoted as δ_{lag} and is measured in degrees. This is the amount of surface travel that corresponds to the maximum valve displacement from neutral and represents the maximum position increment that the surface may lag the pilot input command. The time lag and position lag are directly related via the maximum surface rate (rate limit). Thus the time lag T_{lag} is the position lag δ_{lag} divided by the *surface rate limit* $V_{\max}$

$$T_{\mathrm{lag}} = \frac{\delta_{\mathrm{lag}}}{V_{\max}}$$

It is important to note that the position lag is measured in position units and that pilot force inputs are not necessarily relevant. No matter how hard the pilot pulls or pushes he or she can only bottom the valve, which is a hard constraint. In fact, one reason that over-driven valves and other schemes ultimately replaced the hard limits implicit in the Fig. 3 system was the occasional valve damage that overactive pilots exerted on the early systems.

When fully powered systems were in their early phases of development, a great deal of analytical and experimental effort was spent to determine desirable values for the three key parameters: time and position lags and maximum surface rates. These quantities are among the central design and dynamic features of fully powered actuators. Pilot control factors, including PIO tendencies, were major considerations. Remarkably, pilot preferences, especially fighter pilots and helicopter pilots, typically support far higher surface rates than are theoretically needed even in quite drastic maneuvers. Pilots tended to dislike the valve-bottoming cue and, to avoid it, demanded faster surface rates than an equivalent automatic system could effectively use. This is often the bane of surface actuator designers who are concerned with weight, volume, and power demands. On the other hand, there are several instances where a too-conservative "solution" that settled for lower surface rates resulted in a quite dramatic rate-limited PIO (e.g., the North American X-15 first flight PIO). Consequently, as a result of a great deal of experimentation on a large number of aircraft, some examples of desirable rates and lags have gradually emerged. For example, desirable surface rates for fighter aircraft are, from stop to stop: 1 s (elevator) $\frac{1}{2}$ s (aileron), and 1 s (rudder) [14].

V. Smart-Cue and Smart-Gain Concepts

In this section, the ideal control system paradigm is used to develop the smart-cue and smart-gain concepts.

A. Smart-Cue

The basic idea in applying the ideal system concept is to restore a force feedback cue akin to the ideal valve-bottoming characteristics in a FBW system configuration. This is the heart of the smart-cue concept. Note that smart-cue can be applied to non-FBW manual control systems as well; however, the implementation may be more hardware intensive. As shown in Fig. 5, the commanded surface position and actual surface position are used to define a position error via an ideal linear system that can be as simple as a unity gain. Comparisons of the position error with idealized manual control system characteristics (i.e., position lag) will therefore reflect differences, due to distortions in the actual system. Cuing and corrective forces, the smart-cue, are then presented to the pilot as a proprioceptive display. Nominally the mechanization of this feature will be based on a manipulator with back-drive capability. In principle, the back-drive mechanism is an adjustable spring gradient artificial feel system force producer that constitutes a proprioceptive display.

Consider, as the prime example, rate limiting in the actuator. This is the most pervasive and awkward to handle manual control system distortion. As a source of category II PIOs it is also probably the most commonly encountered controls-related PVS safety issue. In an ideal emulation the spring gradient would be that appropriate to the particular control surface within the range of PVS linear operations. Then, when the pilot control input signal calls for surface rates that exceed the velocity limit, the force feedback will be increased and, in the utmost implementation, can simulate a valve-bottoming virtual stop. For the extreme case that emulates valve bottoming this has the following effects:

1) The pilot is cued to the presence of dynamic distortion due to rate-limiting.

2) The pilot control input and the surface output are essentially locked together as long as the distortion persists.

3) The control surface position lags the pilot command by the position lag (δ_{lag}).

4) The time delay between the pilot and the surface is constrained to be no more than the time lag (T_{lag}) as long as the distortion persists.

As a practical matter in the absence of an actual physical stop it is difficult to mechanize exactly the essentially infinite spring gradient character of the virtual stop corresponding to valve bottoming. However, an extreme and sudden change in the effective gradient is entirely feasible. For example, increases in effective stick force gradient with adjustable force producers are commonplace.

Although the fundamental concept has remain fixed, many options remain regarding how the concept is mechanized and integrated within a modern flight control system that include the following:

1) *Design of the alerting function*: This includes selecting position lag and related values and determining how to turn the force feedback

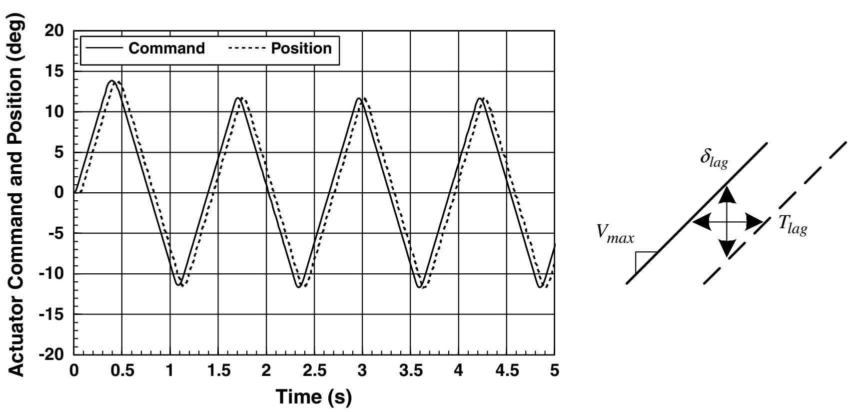

Fig. 4 Input/output comparisons for a valve-bottoming actuator.

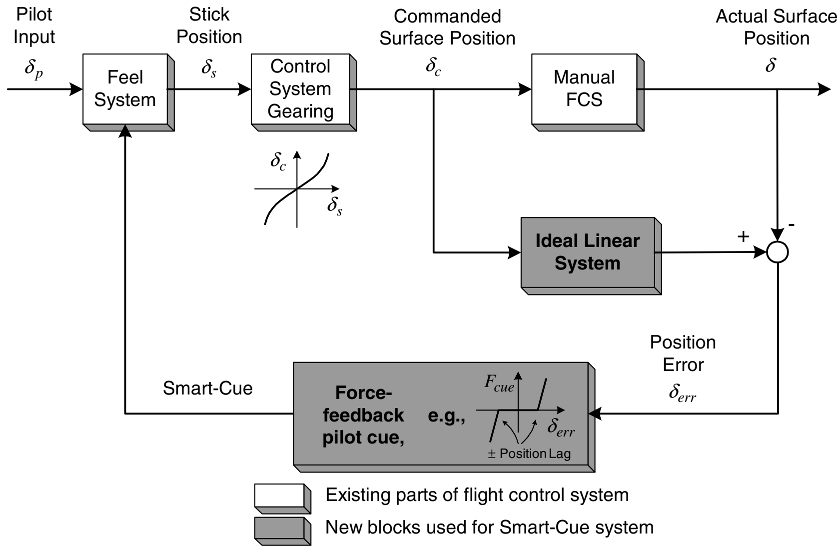

Fig. 5 Implementation of the smart-cue system.

on and off. This is the heart of the mechanization issue that can mean the difference between a highly effective cue and a nuisance or worse.

2) *Design of the constraining function*: This includes selecting the level of force feedback from gentle resistance to hard stops that emulate the valve-bottoming effect. Because the degree of force feedback will be a function of the amount of identified dynamic distortion as measured by the position error, variable force feedback gradients are possible as well.

The fundamental design concept, providing a force feedback cue to the pilot based on a measure of dynamic distortion (the smart-cue), has thus been established.

Piloted simulation was used to evolve the smart-cue mechanizations that were eventually evaluated in-flight. A number of feedback force options were considered individually and in various combinations. Options included a force that produced an effective spring gradient change, a coulomb friction force, and damping forces based on control stick velocity and the rate of change of position error. The gradient force was found to be effective for pitch axis evaluations, but high frequency oscillations associated with the limb-manipulator mode [15] regularly occurred in the roll axis. No such oscillations accompanied the friction force in either axis. The damping forces did not yield useful results and were thus eliminated from the mix. The best results in the simulator were obtained in both axes for runs involving combined gradient and friction forces.

B. Smart-Gain

A second design concept that is also based on a measure of dynamic distortion (the smart-gain) evolved from the checkout flight process. A discussion of the flight-test process is beyond the scope of this paper. The reader is referred to [2], the companion paper, for further details. In short, the Calspan Learjet II in-flight simulator was used to conduct both the checkout flights and formal evaluations. In the checkout flight process, several smart-cue mechanizations were found to work well for the cruise evaluations. Results of the precision offset landing task were less certain. First, the evaluation pilot appreciated that the smart-cue gave an apparent "trough" in which it was safe to move the stick in the presence of control surface rate limiting. The size of the trough was more pronounced when the cuing force was increased as a function of position error. A cuing force level could not be found, however, that allowed the pilot to comfortably make roll axis corrections without "fighting" the smart-cue forces. Still some improvements with the cuing were observed. These results led to a postflight debrief discussion of possible command path gain adjustments as an alternative to the high feedback forces.

Piloted simulation was used to rapidly prototype such a concept, the smart-gain. Past work including the PIOS filter [4] used on the space shuttle employ command path gain reduction techniques. Such techniques estimate the frequency of the pilot's input and then attenuate the input as a function of this frequency. This technique does not, however, take the response of the control system into consideration, and so the pilot input is attenuated whether or not it is needed. With the smart-gain, the pilot input is attenuated as a function of the position error, the measure of dynamic distortion, as shown in Fig. 6. A position lag metric is used to turn the smart-gain on and off. The position lag may be set independently to the values used for the smart-cue.

The smart-gain was found to be a critical innovation. As described in [2], repeated successful landings were accomplished during the formal evaluation process with the best results coming from a smart-cue/smart-gain combination.

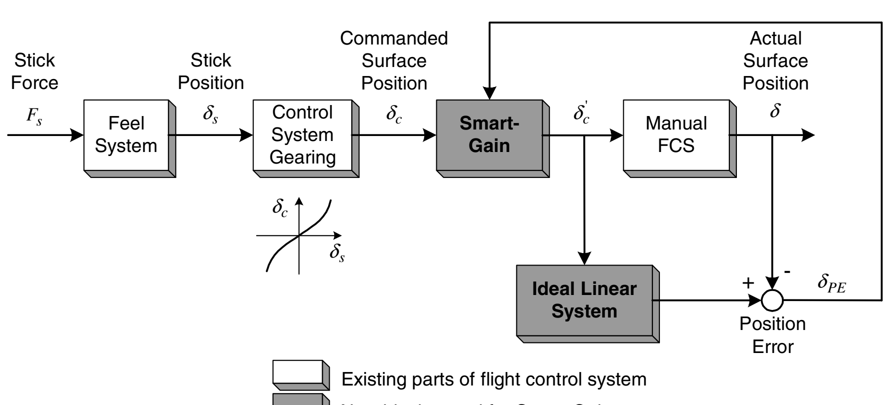

Fig. 6 Implementation of the smart-gain system.

VI. Conclusions

This paper described the development of an innovative means to alert, constrain, and thereby alleviate loss of control associated with unfavorable pilot–vehicle systems interactions including pilot-induced oscillations that are often present in high gain, closed-loop operations. It has often been tacitly assumed that the adoption of fly-by-wire systems has eliminated the primary manual control link as an important player in loss of control situations. Ideal pilot-to-surface relationships were used to measure the impact of control system effects, such as control surface rate limiting, that distort the actual control system response. The position error of this dynamic measure of this dynamic distortion was used to develop 1) a command path gain adjustment mechanism, a smart-gain, and 2) active alerting and constraining proprioceptive and tactile feedback cues to the cockpit controller, a smart-cue, when predetermined dynamic distortion boundaries, the position lag metric, are exceeded. The smart-gain and smart-cue concepts were developed and refined via piloted simulation. Flight-test evaluations were then conducted with a variable stability in-flight simulator. When used together the smart-gain and smart-cue were found to enhance flight safety by significantly reducing pilot–vehicle system loss of control incidents.

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