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A Handling Qualities Assessment of a Business Jet Augmented with an $\mathcal{L}_1$ Adaptive Controller*

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This paper presents a simulation handling qualities assessment for a small business jet augmented with an $\mathcal{L}_1$ adaptive flight control system. In particular, the main objective of the study is to investigate the ability of $\mathcal{L}_1$ adaptive control to improve aircraft handling qualities and prevent unfavorable aircraft-pilot interactions in the presence of aircraft failures. The experiments have been conducted on the motion-based SIMONA Research Simulator at the Delft University of Technology in The Netherlands. The preliminary results presented in this paper suggest that $\mathcal{L}_1$ adaptive control is able to provide consistent aircraft handling qualities in the presence of faults and failures and in different atmospheric (turbulence) conditions.

I. Introduction

Aircraft loss-of-control (LOC) remains a major cause of fatal accidents across all vehicle classes and operational categories [1,2]. Contributing factors to LOC include, but are not limited to, component failures, structural damage, upset conditions due to abrupt maneuvers, wind shear, turbulence, or wake vortices, and icing conditions altering the aircraft's aerodynamic properties. These disturbances can force the aircraft out of the normal flight envelope and hinder the pilot in effectively controlling the aircraft in the new situation. Augmenting the aircraft with a flight control system (FCS) to support the pilot in these off-nominal conditions has the potential to reduce these types of LOC incidents. However, LOC prevention and recovery capabilities of current conventional FCSs are very limited, especially in unforeseen circumstances (e.g. control surface failures or vehicle damage). In such situations, FCSs that are able to adapt to the altered aircraft dynamics can provide the pilot with safe and predictable handling qualities.

Previous work by the authors has shown that implementation of an $\mathcal{L}_1$ adaptive FCS onboard an aircraft may give the opportunity to maintain stability and improve aircraft performance at challenging flight conditions or in the event of control surface failures and aerodynamic stability degradation [3–7]. In fact, $\mathcal{L}_1$ adaptive FCSs have been shown to be capable of compensating for unexpected, unknown, severe failure events, while delivering predictable performance and handling qualities across the flight envelope without enforcing gain-scheduling of the control parameters, persistency of excitation, or control reconfiguration. Also, a *graceful* degradation in performance and handling qualities has been observed as the faults and failures impose more and more severe limitations on the (dynamic) controllability of the aircraft.

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(a) SRS exterior.

(b) SRS flight deck with the hydraulic control column.

Figure 1: Simona Research Simulator (SRS).

Figure 2: Cessna Citation II flying laboratory aircraft.

This paper presents preliminary handling qualities experiment results for a small business jet aircraft model augmented with an $\mathcal{L}_1$ adaptive FCS. The main objective of this study is to investigate the ability of an $\mathcal{L}_1$ adaptive FCS to provide predictable performance with consistent handling qualities in the presence of failures and in different atmospheric (turbulence) conditions. The handling qualities assessment has been conducted through piloted-simulation evaluations on the SIMONA (SImulation, MOtion, and NAvigation) Research Simulator (SRS) at the Delft University of Technology in The Netherlands [8]. The SRS is a research flight simulator with configurable flight deck instrumentation systems, wide-view outside visual display system, electrically loaded sidestick controller and hydraulic six-degree-of-freedom (6DOF) motion system, shown in Figure 1. The aircraft model is based on that of a Cessna Citation I, which is similar to the TU Delft's Cessna Citation II flying laboratory aircraft (Figure 2). The evaluation task used for the handling qualities assessment is an offset approach and landing, with tightly specified performance criteria, and was performed by three pilots with extensive experience as captain on the Cessna Citation II. This experiment also serves as a first step towards flight testing the $\mathcal{L}_1$ adaptive FCS on the TU Delft's research aircraft.

This paper is organized as follows. First, to place the present study into the appropriate context, Section II provides a brief overview of $\mathcal{L}_1$ adaptive control and the piloted flight tests on the NASA AirSTAR research aircraft. Then, Section III describes in detail the handling qualities experiment conducted on the SRS, the results of which are presented in Section IV. Section V includes a discussion of these results and, finally, Section VI contains the main conclusions and describes future research plans.

II. Background

Adaptive control has long been seen as an appealing technology with the potential to reduce loss-of-control type accidents and improve aircraft handling qualities by reducing pilot workload during challenging flight conditions and in the event of severe failures or vehicle damage. However, several limitations of the conventional adaptive systems have prevented this technology from being widely used in safety-critical aerospace applications. In particular, the key deficiencies of conventional adaptive control systems are: (i) the lack of predictability of the closed-loop response due to unforeseeable interactions between the adaptation process, the uncertainty dynamics, and the feedback loops; (ii) the limited framework for analysis of the robustness and performance guarantees of closed-loop adaptive systems; (iii) the lack of systematic design guidelines to solve the tradeoff between adaptation, performance, and robustness; and (iv) the inability to identify and compensate for the undesirable effects of general ("non-cascaded") unmatched uncertainties in the system dynamics.

These limitations have been overcome by the theory of $\mathcal{L}_1$ adaptive control, a method for the design of robust adaptive control architectures using fast adaptation schemes [9]. The key feature of $\mathcal{L}_1$ adaptive control is the decoupling of the adaptation loop from the control loop, which enables fast adaptation without sacrificing robustness. In fact, in $\mathcal{L}_1$ adaptive control architectures, the rate of the adaptation loop can be set arbitrarily high, subject only to hardware limitations –computational power and high-frequency sensor noise–, while the tradeoff between performance and robustness can be addressed through conventional methods from classical and robust control. This separation between adaptation and robustness is achieved by explicitly building the robustness specification into the problem formulation, with the understanding that the uncertainties in any feedback loop can be compensated for only within the bandwidth of the control channel. From an architectural perspective, this modification of the problem formulation leads to the insertion of a bandwidth-limited filter in the feedback path, which ensures that the control signal stays in the desired frequency range. On one hand, the fact that the adaptation rate can be arbitrarily high allows for compensation of the undesirable effects of rapidly varying uncertainties and significant changes in the system dynamics. Fast adaptation is also critical to achieve predictable transient performance for system's both signals, input and output, without enforcing persistency of excitation or resorting to high-gain feedback. On the other hand, the bandwidth-limited filter keeps the robustness margins bounded away from zero in the presence of fast adaptation schemes. To this extent, the bandwidth and the structure of this filter define the tradeoff between performance and robustness of the closed-loop adaptive system. These features of $\mathcal{L}_1$ adaptive control have been verified *–consistently with the theory–* in a large number of flight tests and mid- to high-fidelity simulation environments (see for example [3–5, 7, 10–14]).

Of particular interest in the context of this paper are the flight tests of an $\mathcal{L}_1$ adaptive flight control system on the NASA AirSTAR GTM aircraft, conducted as part of the IRAC Project (2007–2010). The IRAC Project, which was created by the NASA Aviation Safety Program, had as one of its primary objectives to advance and transition adaptive flight control technologies as a means of increasing aviation safety. To this end, NASA developed the AirSTAR Flight Test Facility, integral part of which is the GTM aircraft. The GTM is a remotely piloted, twin-turbine-powered, and dynamically scaled model of a civil transport aircraft, designed to provide a flexible research environment with the ability to conduct rapid prototyping and testing for control algorithms in extremely adverse flight conditions, such as in-flight failure emulation and flight at high risk upset conditions.

The $\mathcal{L}_1$ adaptive flight control system was flown at the NASA Wallops Flight Facility, VA, in September 2009, and at Fort Pickett, VA, in March, June, and September 2010, and in May 2011. These flight tests demonstrated that, in the presence of aircraft component failures and significant changes in aircraft dynamics, the $\mathcal{L}_1$ flight control system is able to maintain aircraft safe operation and predictable performance with reduced pilot workload during both standard flight conditions and unusual flight regimes, like stall and post-stall. Moreover, the $\mathcal{L}_1$ flight control law is currently being used at NASA LaRC to support unsteady aerodynamic modeling work at challenging flight conditions, such as stall and post-stall, and also has enabled real-time dynamic modeling of the departure-prone edges of the flight envelope. The $\mathcal{L}_1$ control law supports these modeling tasks by allowing the research pilot to operate the aircraft in precarious flight conditions near stall and departure for longer periods of time, which provides time for the optimized multi-input wavetrains to excite the aircraft dynamics in all 6DOF to collect the data needed for real-time dynamic modeling. Details about the design and performance of the $\mathcal{L}_1$ adaptive flight control law for the GTM aircraft can be found in [4,5,7,14].

One of the underlying assumptions for the AirSTAR flight tests is that, for both the "healthy" and impaired aircraft configurations, the (remaining) control authority is enough to maintain controllability of the aircraft at the flight condition where the failures are engaged. This assumption also holds for the experiment on SRS reported in this paper. While it is clear that post-failure flight safety depends on the ability to estimate the achievable flight envelope of the impaired aircraft, the development of real-time schemes for *flight-envelope determination and protection* is beyond the scope of this paper. Future research will aim at developing techniques for flight-envelope estimation and protection, as well as their integration into a fault-tolerant $\mathcal{L}_1$ adaptive flight control system.

In this paper, we present preliminary results of a new effort in the development, flight verification and validation, and technology transition of $\mathcal{L}_1$ adaptive control to general aviation aircraft. This effort is of particular interest, as it is the first time a rigorously designed $\mathcal{L}_1$ adaptive flight control system is tested on a 6DOF motion-based simulator. By adding motion cues and low-latency wide field-of-view visual cues, the evaluation pilots are immersed in a realistic flight environment, enabling them to better assess the aircraft handling qualities with and without failures, as well as its transient responses during the failure in a way that is representative of actual flight tests. In particular, any unwanted transients or highly dynamic control deficiencies that are difficult to observe from pure visual cues can be found through the motion cues. The results presented in this paper are the first of a series of experiments that try to evaluate the impact of an $\mathcal{L}_1$ adaptive augmentation control loop on the handling qualities of a small business jet in the presence of faults and failures, and represent a first step towards flight testing an $\mathcal{L}_1$ adaptive flight control system on the TU Delft's Cessna Citation II flying laboratory aircraft.

III. Experiment

The main objective of the study is to investigate the ability of an $\mathcal{L}_1$ adaptive FCS to provide enhanced handling qualities and maneuverability margins for *safe landing* in the presence of failures and in different atmospheric conditions. The aircraft model used is based on that of a Cessna Citation II-like aircraft. Next, we describe the evaluation task used for handling qualities assessment, and provide details about the different configurations tested as well as the performance measures used to evaluate these configurations.

III.A. Task

The evaluation task used for the experiments is an offset approach and landing, with tightly specified performance criteria (see Figure 3). The same task has previously been used for handling qualities evaluations of a large transport aircraft in real fight and in the SRS [15]. Each run starts fully trimmed in approach configuration (120 kts) at 1000 ft while descending along the glideslope. The aircraft is lined up along a drainage ditch with a 300 ft lateral offset with respect to the localizer. The pilot is required to follow the glideslope until 200 ft, while visually following the drainage ditch. At 200 ft a correction initiation command is given, after which the pilot has to execute a step both laterally and vertically in order to line up with the runway, flare and touchdown in accordance with the performance criteria. Below 200 ft the pilot is free to perform any action necessary, including reducing power and leaving the glideslope. This maneuver serves to severely tax the aircraft-pilot system in the roll and pitch (flare) channels in order to bring out any unwanted handling qualities deficiencies in the system.

III.B. Independent Variables

In order to evaluate the ability of $\mathcal{L}_1$ adaptive control to provide consistent aircraft handling qualities in the presence of faults and failures, the offset landing task described above is to be tested with the aircraft augmented with an $\mathcal{L}_1$ adaptive FCS in both the presence and absence of failures. To validate and value these results, the same offset landing task is flown with the aircraft augmented with other non-adaptive flight control systems for the same failure configurations. The handling qualities evaluations are also repeated in moderate turbulence conditions. The presence of turbulence forces the pilot to actively and tightly close

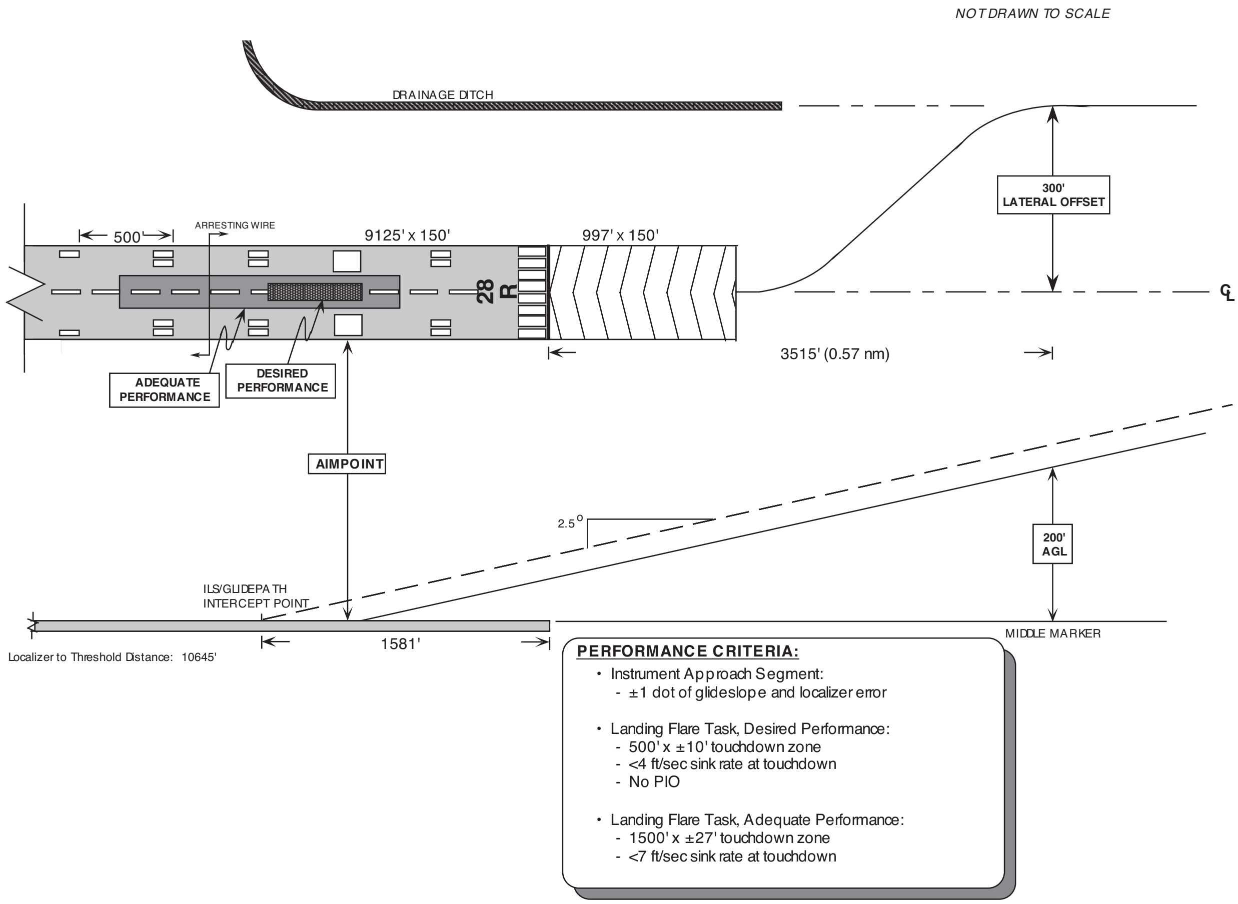


Figure 3: Offset approach and landing evaluation task and performance metrics, figure taken from [15].

the control loop, which is expected to add to the workload. *Flight control system*, *failures*, and *turbulence* become thus the three independent variables of this experiment.

III.B.1. Flight Control System

For this experiment, three flight control systems have been considered that generate control surface deflection commands for elevators, ailerons, and rudder in response to pilot stick and pedal commands and aircraft state data. These three control laws include (*i*) a revisionary stick-to-surface (S2S) control, (*ii*) a non-adaptive baseline (BL) controller, and (*iii*) an $\mathcal{L}_1$ adaptive augmentation loop. The $\mathcal{L}_1$ adaptive control loop is implemented as an augmentation of the non-adaptive baseline controller, and therefore, if the adaptive loop is active, the baseline controller is also active.

When the *S2S mode* is active, the pilot uses longitudinal stick, lateral stick, and pedals to directly command elevator, aileron, and rudder deflections, respectively. The only feedback loop involved is a yaw damper augmenting dutch roll stability (see Figure 4). This flight control mode corresponds to the current conventional control architecture during normal operation of the TU Delft's Cessna Citation II flying laboratory aircraft.

The *baseline controller* is designed to provide the necessary stability augmentation and sufficient command response bandwidth for normal aircraft operation during take-off, cruise, and landing. The longitudinal axis control consists of a pitch damper augmenting short period stability, while the lateral-directional axis control consists of a yaw damper/sideslip PI-controller providing control of sideslip angle while augmenting the dutch roll stability. The pilot, thus, uses longitudinal and lateral stick to directly command elevator and aileron deflections, and uses the pedals to command a desired angle of sideslip. Figure 5 shows the block diagram of the developed baseline controller, the structure of which is inspired by the work reported in [16].

The $\mathcal{L}_1$ *adaptive control loop* is implemented as an augmentation of the baseline controller described above, and it is based on the theory presented in [17]. The objective of the adaptive loop is to improve robustness of the augmented aircraft to system uncertainties, while maintaining the same level of performance provided by the baseline controller in nominal operating conditions. The state predictor of the $\mathcal{L}_1$ adaptive control law is based on reduced linearized dynamics of the augmented aircraft at different flight conditions. For the longitudinal channel, these reduced dynamics include only the short-period dynamics of the airplane; for the lateral-directional channel, the state predictor includes four aircraft states, namely, roll rate, yaw rate, sideslip angle, and bank angle, as well as the two baseline controller states, the yaw-damper washout state and the sideslip-angle integral state. The estimation loop of the $\mathcal{L}_1$ controller is based on piecewise constant adaptation laws, which update the uncertainty estimates at 200 Hz (adaptation sampling time of 5 msec). Finally, overdamped second-order lowpass filters with unity dc gain are used in all control channels. We notice that the same parameters for the adaptation rate and the lowpass filters are used across the entire flight envelope, with no scheduling or reconfiguration. Figure 6 shows the general structure of the $\mathcal{L}_1$ adaptive loop augmenting the baseline controller.

The design of the control loops for the three control modes is based on linearized models of the airplane at different airspeeds, a fixed altitude, two flap angle settings (no-flap and full-flap), and landing gear up. The feedback gains of these control loops are thus scheduled against airspeed or flap angle setting. On one hand, the yaw damper of the S2S mode is scheduled against airspeed to provide a uniform dutch roll damping throughout the flight envelope. On the other hand, for the design of the baseline controller and, consequently, the $\mathcal{L}_1$ adaptive control loop, the flight envelope is partitioned based on airspeed into cruise and landing flight conditions. For cruise flight conditions, some of the feedback gains are scheduled separately against airspeed, while other gains are set to constant values (e.g. the gains of the sideslip PI-controller). For landing flight conditions, some of these feedback gains are also scheduled against flap angle setting. Details of the implementation of the baseline controller and the $\mathcal{L}_1$ adaptive augmentation loop will be published elsewhere.

III.B.2. Failures

In the experiment, only one particular aerodynamic failure was introduced. When activated the longitudinal static stability derivative C_{m_α} and the lateral roll damping stability derivative C_{l_p} were artificially degraded through a destabilizing feedback loop. The values for these stability derivatives were reduced with 75% of the value under the governing flight condition. It must be noted that the intention was to present the evaluation pilot with an aircraft configuration that exhibits challenging stability deficiencies. For this first experiment no attempt was made to introduce a failure representing a physical aircraft malfunction.

III.B.3. Turbulence

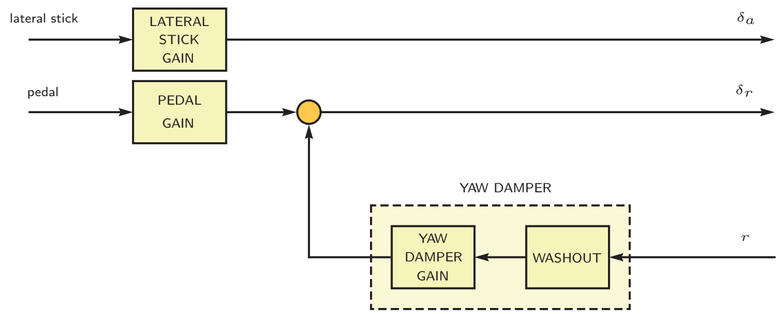
The task is flown with and without atmospheric turbulence. No wind is present in either case. The turbulence model uses a constant Dryden spectrum over the entire flight and is of moderate intensity. No patchiness or ground interaction is incorporated.

III.C. Dependent Measures

For each configuration of independent variables, the following dependent measures are recorded:

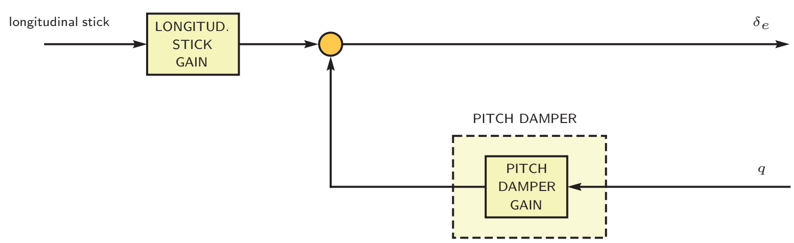
- Performance measures:
  - Touchdown sinkrate (ft/s),
  - Touchdown position (ft).
- Cooper-Harper ratings, with performance criteria as detailed in Section III.A.
- Pilot comments.

(a) Longitudinal channel

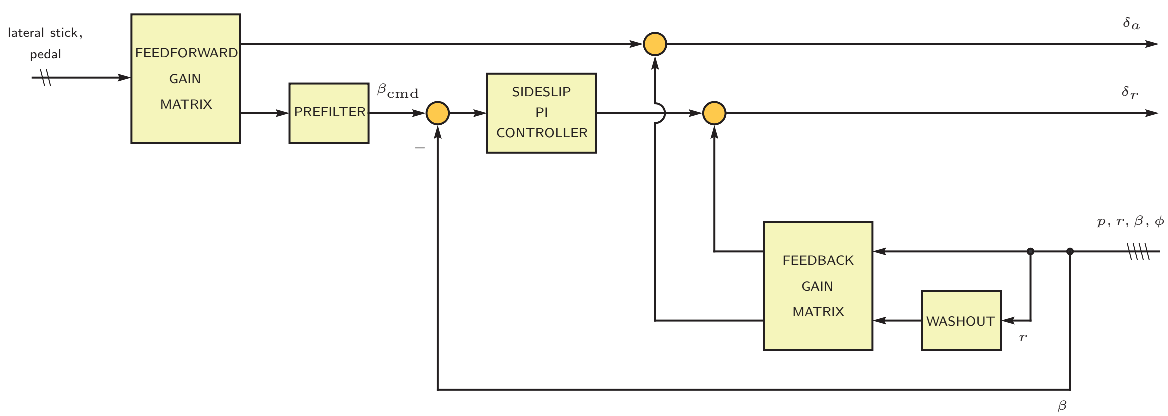


(b) Lateral-directional channel

Figure 4: Stick-to-surface control architecture.

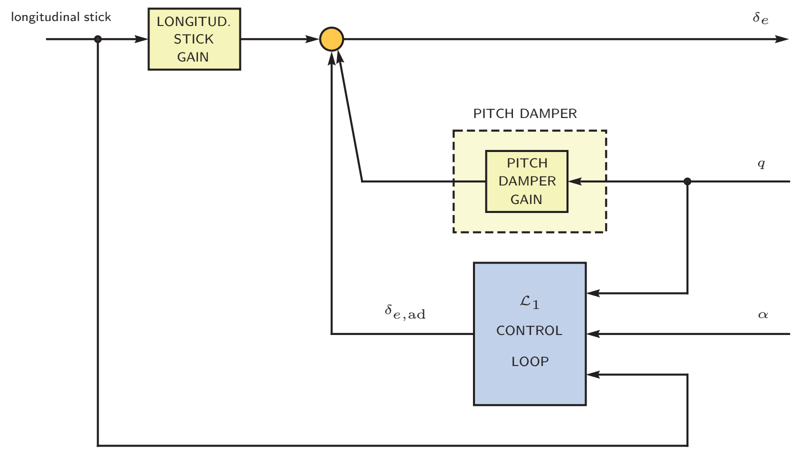


(a) Longitudinal channel

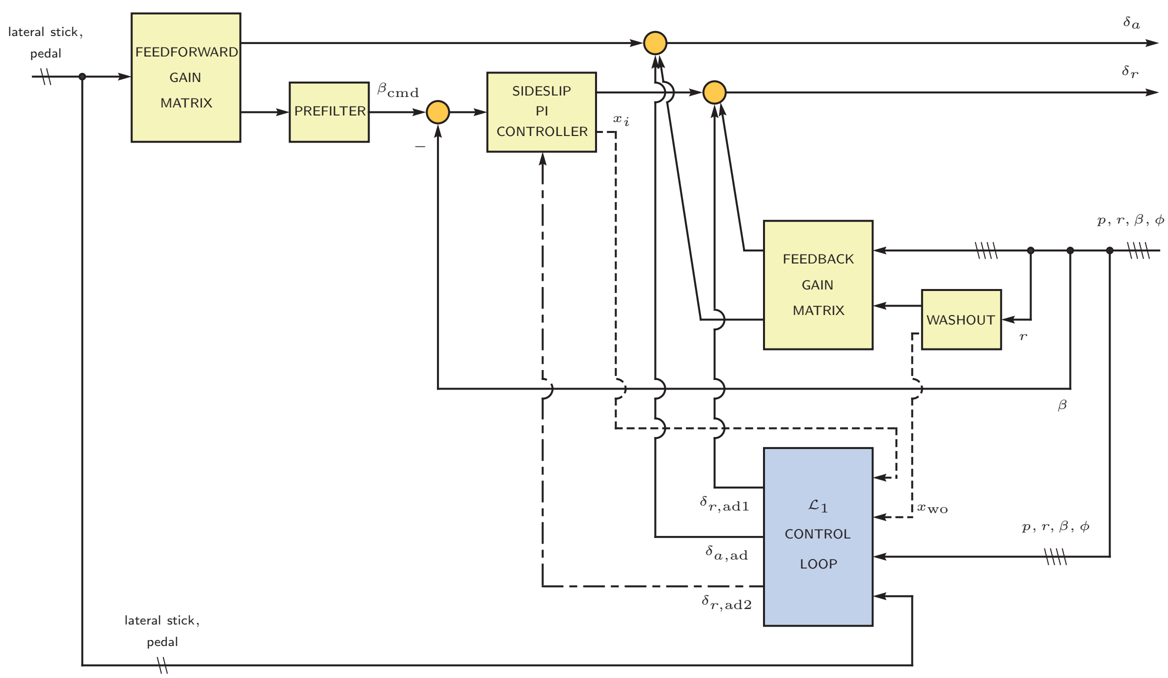


(b) Lateral-directional channel

Figure 5: Baseline control architecture.



(a) Longitudinal channel



(b) Lateral-directional channel

Figure 6: Baseline control architecture with $\mathcal{L}_1$ adaptive augmentation loop.

III.D. Hypotheses

For the offset landing task described above, and based on the expected behavior of the different flight control systems, we pose the following hypotheses:

1. The Cooper-Harper ratings of the $\mathcal{L}_1$, BL, and S2S flight control modes are equal for those flight conditions without failure.

2. The Cooper-Harper ratings of the BL controller are equal to those of the S2S controller for the flight conditions with failure.

3. The Cooper-Harper ratings of the $\mathcal{L}_1$ adaptive FCS are lower (better) than those for the BL and S2S flight control modes for the flight conditions with failure.

4. The hypotheses above hold for the conditions with and without turbulence.

III.E. Apparatus – SIMONA Research Simulator

The SIMONA Research Simulator is used to perform the experiment. Its flight deck is configured to match a Cessna Citation II as closely as possible. The aircraft's instrumentation is recreated on the simulator's main instrument panel and the collimated $180° \times 40°$ outside visual shows an airfield with the reference drainage ditch offset from the runway center line. Due to limited availability of the control loading system, the pilots use an electrically loaded active side-stick and spring loaded rudder pedals instead of a conventional control column, as installed in the original aircraft. The sidestick's sensitivity is tuned for comfortable flying, while still allowing sufficient excursions to perform the sidestep maneuver.

The simulator's motion system is tuned to give the pilot sufficient motion cues to perform the task while still remaining within the available motion space. The motion filter is of a classical form [18] and tuned with a focus on longitudinal motions, as shown in Table 1:

Table 1: Motion filter parameters.

	gain	high-pass break frequency [rad/s]
Surge	0.7	2.0
Sway	0.5	4.0
Heave	0.5	2.0
Roll	0.7	4.0
Pitch	0.7	1.0
Yaw	0.5	2.0

The mathematical model simulation runs at a rate of 1000 Hz. The motion cueing, control loading software and data logging run at a rate of 100 Hz, and all displays run at 50 Hz.

III.F. Subjects

Three pilots participate in the experiment, all of them with extensive experience as captain on a Cessna Citation. The average pilot age amounts to 57.7 years with a standard deviation of 20.6 years, while the average total flying hours is 8700 hrs with a standard deviation of 6000 hrs.

III.G. Experimental Procedure

To prevent learning effects, the experiment starts with a session in which both the task and the evaluation with the Cooper-Harper rating scale are trained with the S2S configuration. After the training the 12 experimental conditions are performed twice, with the drainage ditch on the left and right side of the runway. The 24 runs are presented in a random order. Where applicable, the failure is engaged immediately after

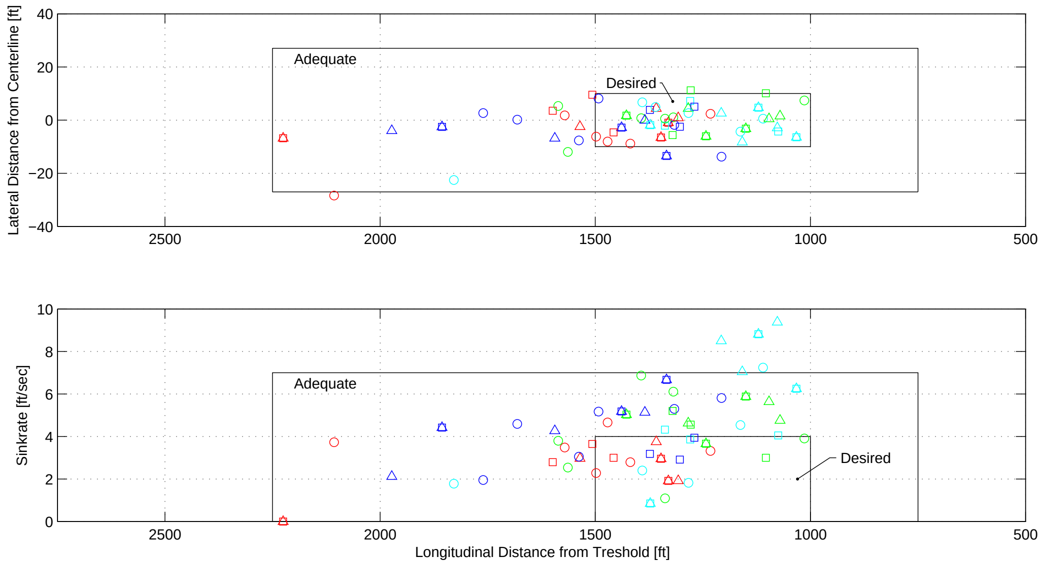


Figure 7: Touchdown performance of all evaluation runs (△ = S2S, □ = Baseline, ◯ = $\mathcal{L}_1$, red = without failure & without turbulence, green = without failure & with turbulence, blue = with failure & without turbulence, cyan = with failure & with turbulence).

the FCS is engaged. The pilot has no knowledge about the FCS or failure that is engaged. Directly after each run the pilot is informed of his performance resulting in a Cooper-Harper rating. In addition all pilot comments are recorded.

IV. Results

IV.A. Performance Measures

Figure 7 shows the achieved touchdown locations and corresponding sink rates for each evaluation run. Three different symbols are used to represent the three different flight control systems (S2S, BL, and $\mathcal{L}_1$), whereas four different colors differentiate the four different evaluation settings (with or without failure *and* with or without turbulence). The flight control systems and evaluation settings were introduced in Section III.B. Also shown are the boxes indicating the desired or adequate performance as specified for this task.

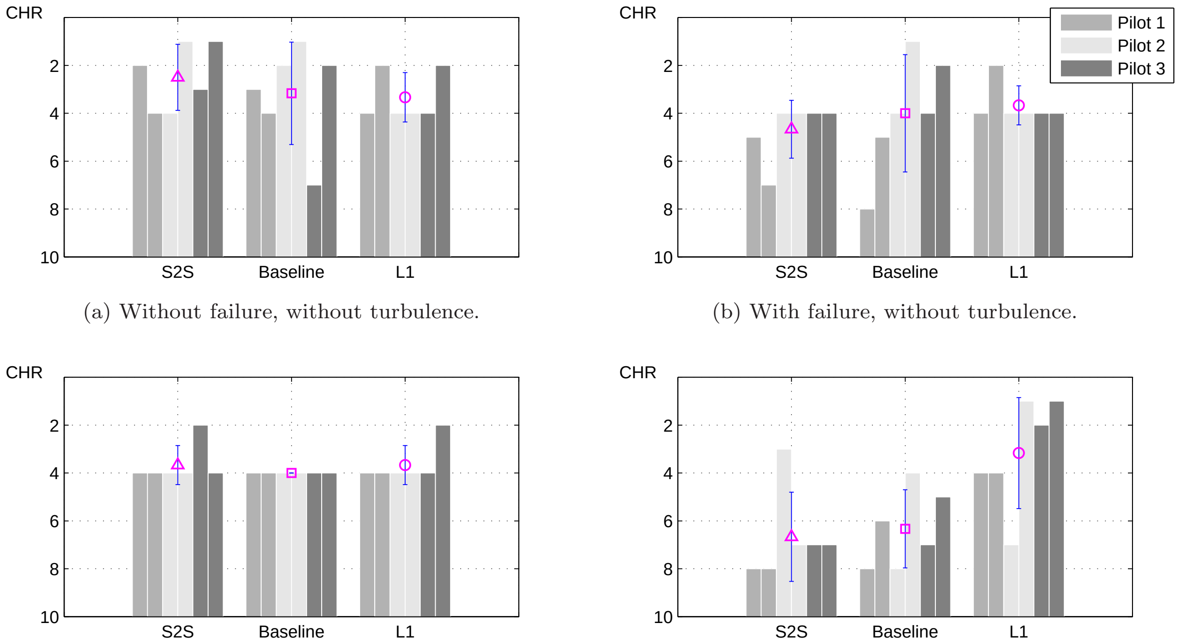
IV.B. Cooper-Harper Ratings

The Cooper-Harper rating for each evaluation run is represented as a vertical bar in Figures 8a-8d, grouped according to the evaluation setting. Each pilot's ratings are colored with the same shade of gray. For each flight control system the mean value of its six evaluations is denoted by the same symbol used in Figure 7. For illustration purposes, the vertical lines indicate the standard deviation within the group of six evaluations.

IV.C. Comments

From the pilot comments it becomes apparent that the failure was especially noticeable in roll. Due to the decreased roll damping, pilots complained about the roll stability during the offset for the S2S and BL conditions. With the $\mathcal{L}_1$ controller engaged, only one pilot mentioned a roll sensitivity problem during one of the $\mathcal{L}_1$ runs with the failure engaged, but generally the pilots did not notice any abnormal roll response in this configuration.

Most comments regarding the $\mathcal{L}_1$ controller concern the pitch control during the flare. The aircraft exhibited unexpected pitch dynamics, sometimes leading to a tendency to float. Similar comments were made about the BL controller in the unimpaired condition. The pilots commented that they were sometimes



(a) Without failure, without turbulence.

(b) With failure, without turbulence.

(c) Without failure, with turbulence.

(d) With failure, with turbulence.

Figure 8: Cooper-Harper ratings for all evaluation runs (△ = S2S, □ = Baseline, ◯ = $\mathcal{L}_1$).

"caught out" by this different behavior during the offset maneuver or the flare itself, because they had not noticed it during the approach phase.

Pilot comments regarding the turbulence indicate that its presence increased their workload and the observability of the failure during the approach and the offset maneuver. In the presence of turbulence, the pilots indicated a preference to land as soon as possible, sometimes at the expense of a higher sink rate.

V. Discussion

As expected by design, the injected failures mainly had an effect in roll by decreasing roll damping. This degradation in roll damping was experienced by the pilots almost exclusively for the S2S and BL flight control modes. The deficiency in roll damping was not noticed when the pilots were flying the $\mathcal{L}_1$ flight control configuration. Apart from the pilot comments, the Cooper-Harper Ratings in Figure 8d show (when turbulence is present) a similar trend of acceptable handling qualities under failure when $\mathcal{L}_1$ flight control is engaged. However, when turbulence is absent, the ability of the flight controller to compensate for the failure did not result in better Cooper-Harper ratings (Figure 8b). Although the pilots did notice a degradation in the roll channel for the S2S and BL control systems (and again no degradation for the $\mathcal{L}_1$ control systems), it did not always lead to excessive increases in workload and poor Cooper-Harper ratings. This result suggests that turbulence is an important independent variable for handling qualities experiments involving failures, as it actively excites the failure and increases the pilot workload during the execution of the task. For the offset approach and landing task used in this study, the turbulence also alerted the pilots to the presence of the failure before performing the sidestep, which allowed them to anticipate the handling during the maneuver.

Another observation from the pilot comments is that the pilots had difficulty controlling the pitch dynamics for both the BL and $\mathcal{L}_1$ flight control systems, especially during the flare, which in most cases prevented them from achieving desired performance. This was contrary to their expectations based on the aircraft handling during the approach phase, in which the pitch handling qualities were judged to be sufficient to achieve desired performance with minimal workload. The pilots, used to the unaugmented Citation II dynamics, had problems in quickly adjusting to the different pitch dynamics of the BL and $\mathcal{L}_1$ flight controllers during the flare. This surprise effect often led to touchdown positions that were long and outside of the desired performance box (Figure 7). Also, most of the landings with desired touchdown positions were accompanied by high sink rates, resulting in overall adequate performance and hence pushing the Cooper-Harper ratings into level 2. A different evaluation technique in which pilots are exposed to a particular controller multiple times before switching to another one may reduce the surprise effect and lead to better performance and possibly more consistent ratings, but it would also virtually eliminate the unpredictability element normally present when failures in the aircraft occur.

The hypotheses posed in section III.D are difficult to reject with sufficient certainty due to the small amount of data gathered in this evaluation. A few trends can, however, be observed:

Hypothesis 1 In the presence of turbulence the ratings of all controllers are very similar, but without turbulence a larger variance is observed. It cannot be confirmed that their handling qualities are equal without the failure.

Hypothesis 2 With turbulence both the BL and S2S controller handle similarly badly, although it is hard to ascertain that they are equal. Without turbulence the handling is rated similar and better, but the variance in rating increases.

Hypothesis 3 Without turbulence the $\mathcal{L}_1$ controller does not seem to handle much better than the S2S and BL controllers under failed conditions, but in the presence of turbulence a noticeable improvement of $\mathcal{L}_1$ over S2S and BL seems apparent.

Hypothesis 4 The presence of turbulence does seem to have an observable impact on the rated handling qualities, even though this effect's statistical significance could not be confirmed. From the pilot comments, this seems to be due to the increased amount of control activity required during the approach and thus an increased exposure to the aircraft's handling qualities.

VI. Conclusions

This paper presented preliminary results of a handling qualities experiment for a small business jet aircraft model augmented with an $\mathcal{L}_1$ adaptive flight control system. The experiment was conducted through piloted-simulation evaluations on the 6DOF motion-based SIMONA Research Simulator at the Delft University of Technology in The Netherlands. The results of the study suggest that $\mathcal{L}_1$ adaptive control is able to maintain consistent aircraft handling qualities in the presence of faults and failures and in different atmospheric (turbulence) conditions. However, more experiments are needed to provide statistically significant evidence to support this claim.

Performance measures and pilot comments from the offset landing task considered for the experiment also seem to indicate that more efforts are needed for the design of the baseline controller. This is expected to have direct impact on the handling qualities with the $\mathcal{L}_1$ adaptive control law. Notice that, since the $\mathcal{L}_1$ flight control system is implemented as an augmentation loop of the baseline controller, the handling qualities provided by the $\mathcal{L}_1$ flight control system are limited by the design of this non-adaptive baseline controller. Therefore, benefits of the $\mathcal{L}_1$ control loop in the presence of failures can only be assessed from its ability to maintain the handling qualities provided by the baseline controller for the nominal aircraft configuration.

Future work will also consider different piloted tasks for handling qualities assessment with other, more physically-inspired failures. Moreover, in preparation for the flight tests on the TU Delft's Cessna Citation II flying laboratory aircraft, efforts will be made to derive a model of the fly-by-wire system installed on this research aircraft. This fly-by-wire system imposes limitations on the aircraft control authority and, therefore, it is important to analyze the implications on the plant dynamics and the constraints that may impose on flight control system design.

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