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Conceptual Design and Evaluation of Upset-Recovery Systems for Civil Transport Aircraft

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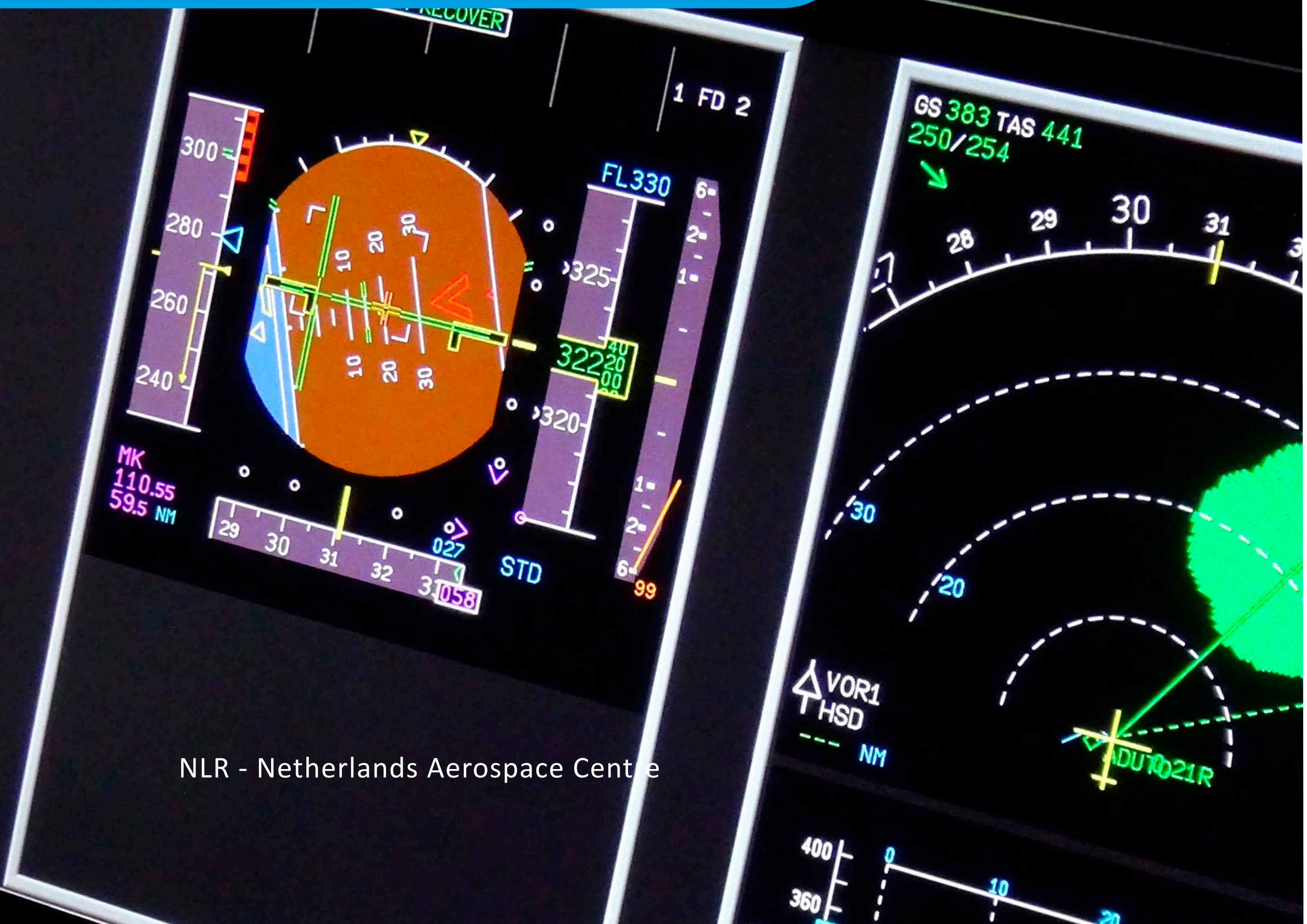

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Conceptual Design and Evaluation of Upset-Recovery Systems for Civil Transport Aircraft

Problem area

Loss of control in-flight (LOC-I) accidents, caused by an upset followed by a failure of the pilot to control and recover the aircraft, remain the largest contribution to fatal aircraft accidents worldwide. A reduction of crew stress (e.g., caused by an unexpected event in a safety critical situation) and high workload will contribute to further reduction of LOC-I related incidents. Modern civil transport aircraft are currently equipped with a flight guidance system that allows the aircraft to be flown automatically for most part of the flight. Future requirements from a flight-deck system-safety point of view include a more integrated design of information systems available to the pilot, including displays and interactions, flight decision support systems (e.g., advisories during upset conditions, including automatic recovery), and the allocation of functions between the pilot and automatic systems during nominal and degraded flight conditions. This new “intelligent” flight deck should be able to sense onboard (flight control) system and environment-induced hazards in real time, and provide the necessary and timely actions to prevent or recover from an upset.

Description of work

The manual-assisted and automatic aircraft upset-recovery system (AURS), as described in this report, was developed as part of a study intended to develop avionics software and systems to enable a higher level of intelligent cockpit

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automation to relieve crew workload and stress under peak operational conditions. The system is designed to recover the aircraft from upsets that bring the aircraft beyond the conventional flight-envelope-protection boundaries that provide a first layer of safety to prevent an upset. Initially, the AURS was developed and demonstrated within the context of reduced crew operations [up to a technology readiness level (TRL) of 3], in which the lack of crew resources (e.g., crew incapacitation) is the most critical in case of emergency situations or degraded flight conditions. The basic AURS was further enhanced to a full manual-assisted and automatic upset-recovery system, as described in this report, including proper human-machine interface (HMI) guidance cues, and evaluated by airline pilots in a dedicated test campaign up to a TRL level of 5.

Results and conclusions

The piloted-simulator evaluation of the AURS showed that the functionalities of the system are able to support pilots during an upset. The pilot's workload was significantly reduced for both manual-assisted and automatic control modes compared to today's situation, in which no guidance is provided for upset recovery. The experiment showed that pilots are willing to rely on the guidance provided by the AURS during an upset. Thereby, it is important for pilots to see and understand what the aircraft is doing and trying to do especially in automatic modes. The study showed that the AURS automatic modes proved to have the highest impact on workload reduction, situation awareness, and stress reduction; thus, future developments for upset-recovery guidance and loss-of-control prevention should focus on automatic-recovery solutions.

Applicability

The developed manual-assisted and automatic upset recovery technology solutions are likely to positively impact the operational safety by means of reduced workload and improved situation awareness. The system can be applied as a standalone, retrofittable, software module that is compatible, and interacts, with existing onboard auto flight systems and/or fly-by-wire systems and navigation/terrain databases of current and future transport aircraft.

GENERAL NOTE

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Contents

Abbreviations

ACRONYM	DESCRIPTION
ANOVA	ANalysis Of VAriance
AP	Auto Pilot
A/THR	Auto THRust
AURS	Aircraft Upset Recovery System
AUTO	AUTOmatic
CARS	Crew Awareness Rating Scale
CFIT	Controlled Flight Into Terrain
DOI	Digital Object Indentifier
FCS	Flight Control System
FD	Flight Director
FL	Flight Level
FMA	Flight Mode Annunciation
FP	Flight Procedure
GRACE	Generic Research Aircraft Cockpit Environment
H	Hypothesis
HMI	Human Machine Interface
HYB-D	HYBrid-Tunnel
HYB-T	HYBrid-Tunnel
kt	Speed unit knots
NLR	Netherlands Aerospace Centre
LOC	Loss Of Control
LOC-I	Loss Of Control In-flight
M	Mach value
MAN-D	MANual-(flight)Director
MAN-T	MANual-Tunnel
Mmo	Maximum Operating air speed in Mach
NASA	National Aeronautics and Space Administration
PFD	Primary Flight Display
p	Statistical significance (probability) level
TLX	NASA Task Load Index
TRL	Technology Readiness Level
UFD	Upset Flight Director
Vmo	Maximum Operating air speed in kts
Vstall	Stalling Speed in kts
z	Z-score

Conceptual Design and Evaluation of Upset-Recovery Systems for Civil Transport Aircraft

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This paper describes the conceptual design and evaluation results of both manual and automatic variants of an aircraft upset-recovery system that has been assessed by experienced airline pilots. The two system variants provide additional layers of protection to what currently exists in aircraft flight-control systems. Apart from the manual pilot-assisted guidance variant, the other variant takes over full automatic control of the aircraft when it accidentally enters an upset due to a range of potentially catastrophic loss of control in-flight scenarios (e.g., crew incapacitation, adverse atmospheric conditions, and onboard system failures). The aim of the piloted-evaluation campaign was to assess the added value of the different upset-recovery-guidance variants in a relevant operational environment, and how well they relieve or assist the pilot in recovering the aircraft, hence bringing the aircraft back into the safe flight envelope following an upset. An initial assessment was made in terms of the preference of the tested automatic upset-recovery system configurations to reduce pilot workload, increase situation awareness, and allow safe interaction with the manual or automated system for upset recovery. The piloted-simulator results show that the functionalities of the system adequately support pilots during upset recovery. Specifically, the automatic modes have the highest impact on workload reduction, situation awareness, stress reduction, and acceptability. The study shows that longer-term solutions for upset-recovery guidance and loss-of-control prevention should focus on automatic solutions in combination with visual-guidance and monitoring cues.

I. Introduction

AN INCREASING number of measures are currently being taken by the international aviation community to prevent loss of control in-flight (LOC-I) accidents involving commercial transport aircraft [1–5]. Conditions that may result in a LOC-I situation (and possible loss of situation awareness [6]) are aerodynamic stalls, extreme atmospheric weather, wake vortices [7], onboard system failures, or an incapacitation of the flight crew (e.g., due to explosive decompression [8]). Aircraft-accident surveys also show cases, in which the fly-by-wire envelope protections have been lost, making the aircraft vulnerable to upsets [9] and stalls [10]. In a LOC-I situation, in most cases, the pilot is not able to adapt to the degraded flight condition or recover from an upset successfully despite the available performance and control capabilities. Recent airliner accident and incident statistics [11] show that, in the period 2007–2016, a total of 16 fatal accidents occurred, resulting in 1345 onboard fatalities, that can be attributed to LOC-I, caused by a piloting mistake (e.g., incorrect stall and recovery procedures), technical malfunctions, or unusual upsets due to external (atmospheric) disturbances. Although LOC-I has become the main cause of fatal aircraft accidents, followed by controlled flight into terrain (CFIT), data examined by the international aviation community show that, in contrast to CFIT, the share of LOC-I occurrences is not significantly decreasing. The actions taken by the aviation community to lower that number do not only include improvements in procedures, training, and human factors, but also finding measures to better mitigate system failures and increase aircraft survivability in case of an accident or degraded flight conditions. The flight-safety community [1,2] has recognized for several years that LOC-I keeps being a major safety concern taking over from CFIT after newly developed terrain warning systems began to mitigate the CFIT risk. Even today, LOC-I accidents caused by a combination of total or partial spatial disorientation followed by a failure to control and recover the aircraft remain the largest contribution to fatal aircraft accidents worldwide [11].

A crew problem or a human-factor issue, such as bad perception of the environment (loss of situation awareness), bad crew coordination, excessive workload, a crew misunderstanding of what is happening (e.g., during an unexpected event), and inappropriate training, can also lead to a LOC-I situation [1,2]. Accidents and incidents are more likely to occur when the situation of the aircraft requires the cockpit crew to perform with a high workload, or when confronted with a surprise event. The reason is that these conditions cause psychological stress, which, in turn, can lead to incorrect actions or omissions in the required procedures. In complex and flight critical situations, it is vital that optimum crew action depends on an adequate understanding of the situation at hand and the corrective actions needed. Future cockpit avionic solutions can play an effective role, due to their long lead time developed in concert with short-term training solutions, by providing the tools and guidance to support the crew's activities, and allowing the interaction between the pilot, the aircraft, and the outside world.

Modern civil transport aircraft are currently equipped with a flight guidance system that allows the aircraft to be flown automatically for most part of the flight. The flight crew, however, is still required to coordinate and manage the overall flight, and to respond to system changes and potential threats as they arise. It is expected that a reduction of crew stress (e.g., caused by an unexpected event in a safety critical situation) and high workload will contribute to further reduction of LOC-I-related incidents. Future requirements from a flight-deck system-safety point of view include a more integrated design of information systems available to the pilot, including displays and interactions, flight decision support systems (e.g., advisories during adverse and/or upset conditions, including automatic recovery),

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and the allocation of functions between the pilot and automatic systems during nominal and degraded flight conditions. This new "intelligent" flight deck should be able to sense onboard (flight control) system and environment-induced hazards in real time, and provide the necessary and timely actions to prevent or recover from any adverse condition. In this context, the challenge faced by today's aviation community is to find new and innovative solutions for future cockpits, supplemented by adequate training, such that the flight crew will be able to operate in all conditions, while ensuring both safer and more efficient flights.

Several recent innovative developments within the aerospace community have shown possible solutions toward the intelligent flight deck to prevent or recover from LOC-I. Damage Adaptive Guidance for Piloted Upset Recovery system provides robust closed-loop upset-recovery guidance, using visual cues, to reduce the effect of inappropriate pilot behavior, and is adaptive to vehicle damage [12]. Automatic upset recovery for large transport aircraft, using features, such as guidance-mode priorities and envelope protection during recovery, has been developed in [13]. In this study, a multimode upset-recovery flight-control system (FCS) was realized and tested in several stall upset scenarios using a state machine to first reduce angular rates and recover the aerodynamic envelope, and then recover the attitude envelope, and finally recover from overspeed. Other examples of piloted evaluated upset-recovery-guidance methods and LOC-I mitigation systems, including an energy-based approach using flight-director guidance cues for stall upsets and methods to prevent unfavorable pilot–vehicle coupling, have been presented in [14,15]. Richards et al. [16] present a method, tested in pilot-in-the-loop simulations, for both manual and automatic LOC-I recoveries, including recovery guidance, for both nominal and off-nominal vehicle dynamics (e.g., system failures). Other studies have shown the effectiveness of new intelligent flight-envelope-protection cues to prevent LOC-I, as presented, for example, in [17].

This paper describes the concept and piloted evaluations of both manual and automatic aircraft upset-recovery systems (AURSs). The new system is characterized as an integral combination of upset-recovery-strategy guidance and control laws (including control-axis priorities and envelope protection), dedicated (more intuitive) human–machine interface (HMI) guidance cues, and extended postrecovery guidance using the existing autoflight and onboard navigation functionalities. In Sec. II, the rationale for the development of the AURS is described, and the problems that currently exist in state-of-the-art aircraft to effectively deal with peak operational conditions or unexpected events that can lead to LOC-I. Section III describes the features of the AURS (providing either manual pilot-assisted guidance or full automatic control when the aircraft accidentally enters an upset), its concept, and modes of operation and cockpit integration. The real-time integration of the AURS for piloted evaluation is described in Sec. IV. This includes the technology setups for the assessment of the AURS functionalities, and experimental objectives and methods. Section V presents the results and observations of the piloted assessment. Conclusions of this study are provided in Sec. VI.

II. Rationale for Upset-Recovery Cockpit Automation and Guidance

Today's commercial aircraft provide a high level of automation and surveillance, allowing the aircraft to navigate automatically from takeoff to landing. The aircraft systems have become highly automated, including complex systems, such as the engines, fuel, and hydraulic systems, and the FCS. Although these technologies have been responsible in the reduction of overall crew workload, aircraft have become more complex and new technologies have been introduced to enable flight in more demanding operational environments, including increased traffic density and adverse weather conditions. This has progressively increased the knowledge required to operate the aircraft, the crew's task being transitioned to a system management and supervisory role, which, in turn, has again raised workload.

The increase in aircraft system complexity has also resulted in failure modes, system anomalies, or mode reversions being more complex or confusing, as indicated in recent accidents and incidents. Increased system complexity also has a significant impact on crew workload, as complex failures can prove more demanding to troubleshoot successfully. The complexity of the situation in combination with high workload has shown to be a contributing factor in the pilot's loss of situation awareness that may ultimately lead to an upset or LOC-I. An example of an incident, in which the aircraft inadvertently entered an extreme upset as the pilot became spatially disoriented while being confronted with a failure situation, is China Airlines Flight 006 [18]. In this case, on 19 February 1985, the aircraft was on a nonstop flight from Taipei to Los Angeles at a cruise altitude of 41,000 ft as the number 4 engine flamed out. As the crew tried to restart the engine, the autopilot tried to maintain a wings-level attitude, while the airspeed continued to reduce without any rudder applied by the pilot. Because of loss of visibility in cloudy conditions and the autopilot being eventually disconnected, the aircraft entered an upset, resulting in a dive at a high bank angle. Without being able to recover from the upset due to lack of any upset-recovery-guidance cues, the aircraft lost 30,000 ft in about 2.5 min with load factors up to $5g$. The aircraft was recovered at 11,000 ft and made a successful emergency landing in San Francisco, while being severely structurally damaged due to loss of parts of the elevators and horizontal stabilizer (Fig. 1, left and center). A typical LOC-I case, in which system complexity left the crew occupied troubleshooting a fault, while the aircraft entered an upset and lost control, is Air Asia Flight 8501 on 28 December 2014 (Fig. 1, right) [19]. The flight originated from Surabaya (Indonesia) and had Singapore as destination. A failure in the rudder travel limiter caused the crew to reset the Flight Augmentation Computer via the circuit breakers in order to try to solve the fault. The electrical interruption caused a mode reversion of the FCS from normal law to alternate law, while the autopilot disengaged and the rudder inadvertently deflected 2 deg to the left. This resulted in a high-bank-angle upset and subsequent stall condition from which the crew was not able to recover. Up to six similar accidents have occurred since 2000, in which loss of situation awareness was the most probable cause of the aircraft entering an unnoticed upset that was not recovered by the crew (e.g., Ethiopian Airlines Flight ET409).

The trend of recent accident and incident cases worldwide shows that the state-of-the-art automation and operations, for current and future demanding operational environments, can be improved further to increase the desired level of operational safety under crew peak workload conditions, specifically in complex situations (e.g., during an emergency) and upset situations. In the event of a failure or human error, the workload sometimes peaks to the point that even a two-pilot crew becomes overloaded. This calls for new and innovative avionics functionalities, with increased automation and better guidance,

Fig. 1 Example aircraft upset and LOC-I incidents and accidents.

combined with improved cockpit displays and human–machine interaction.

The AURS, as described in this paper, was developed as part of a research intended to develop avionics software and systems to enable a higher level of intelligent cockpit automation to relieve crew workload and stress under peak operational conditions. The system is designed to recover the aircraft from upsets that bring the aircraft beyond the conventional flight-envelope-protection boundaries that provide a first layer of safety to prevent an upset. Initially, the AURS was developed and demonstrated within the context of reduced crew operations [up to a technology readiness level (TRL) of 3], in which the lack of crew resources (e.g., crew incapacitation) is the most critical in case of emergency situations or degraded flight conditions. The basic AURS was further enhanced to a full manual and automatic upset-recovery system, as described in this paper, including proper HMI guidance cues, and evaluated by airline pilots in a dedicated test campaign up to a TRL level of 5.

III. Aircraft Upset-Recovery System

The proposed manual-assisted and automatic AURS is a function for any fly-by-wire equipped aircraft that continuously monitors and intervenes when the aircraft enters an upset. The operational causes of flight-envelope excursions and upsets can be a wide variety, as surveyed in Sec. II of this paper.

The AURS allows a fully automatic or manual-assisted recovery from an upset. The system is designed to relieve the pilot/crew from the excessive (and startling) psychological and physiological stresses during an upset to safely recover automatically within the normal operational envelope. The AURS will aid in the manual or automatic recovery of upsets that bring the aircraft outside any flight-envelope-protection logic regime, or when this protection logic is degraded or fully disabled (e.g., when the FCS reverts to direct law during common mode failures). The AURS functionality continuously monitors the flight condition after upset recovery, and may intervene again when a new upset occurs.

A. System Overview

The AURS architecture consists of several software modules, algorithms, and cockpit HMI guidance logics aimed at recovering the aircraft from upsets using manual pilot control guidance or automatic control strategies (Fig. 2). The two variants are set up independent, hence are not combined into a single system (yet). The AURS is used either in the manual mode or in the fully automatic mode. Based on this selected mode, and as soon as the aircraft enters an upset, the AURS strategy and guidance logic recognizes the type of upset and subsequently determines the required control actions to be applied to safely recover and control the aircraft toward the normal operational flight envelope. For automatic upset recovery, the control commands provided by the AURS strategy and guidance logic will be prioritized along the control axes as if they would be applied by a trained pilot. An AURS control logic receives the control demands from the AURS strategy and guidance logic module and directs them to the aircraft control surfaces. Again, based on the selected AURS mode of operation, a new developed dedicated cockpit HMI provides either manual or automatic guidance information to the pilot during an upset of the aircraft. In the manual upset-recovery mode, the demand logic provides recovery guidance via visual steering cues to the pilot presented on the cockpit primary flight display (PFD). Steering cues are derived from the AURS strategy logic. The AURS controller provides the inputs to the demanded sidestick inputs. The AURS visual cues guide the pilot during manual upset recovery by means of a presentation of required steering commands and aircraft operational envelope limits. In the automatic upset-recovery mode, the AURS guidance cues allow the pilot to monitor the performance and mode status of the AURS during actual recovery.

The main features and innovations of the AURS are the following:

1) The system provides automatic and manual-assisted upset recovery modes, with HMI guidance logic and steering cues.

2) In the automatic upset-recovery mode, control-axis prioritization assures that the correct sequence of steering commands is applied to recover from (extreme) unusual attitudes respecting the current operational envelope limitations (in terms of load factor and maximum airspeed).

3) The system provides recovery procedures using load-factor limitation minimizing the potential damage of the aircraft.

4) After automatic recovery, the system commands the autoflight system to steer to a safe operational flight condition (in terms of speed and altitude).

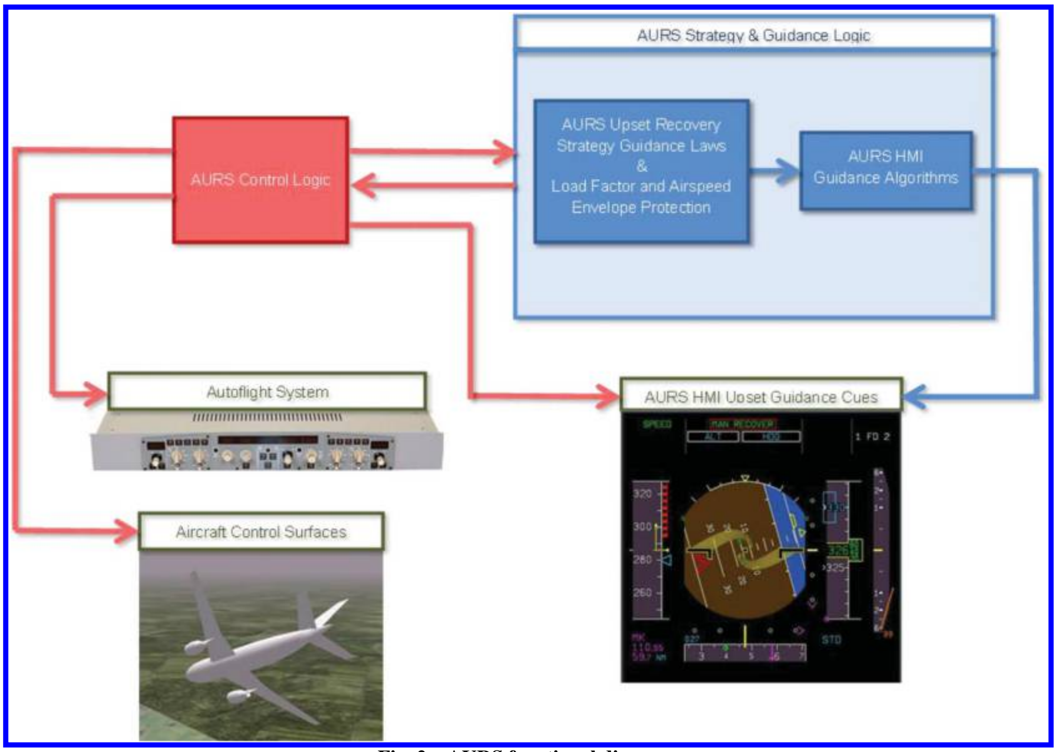

Fig. 2 AURS functional diagram.

5) The system operates in standby mode during (continued) normal flight operations and intervenes when the aircraft enters a new upset.

The AURS system logic consists of the following main modules and algorithms (Fig. 2):

1) An AURS-control-logic module.

2) An AURS strategy and guidance logic module consisting of algorithms (AURS upset-recovery-strategy guidance-law module), which mimic the required upset-recovery control actions as a trained pilot would apply.

3) The AURS-strategy-logic module is build up as a state machine (Fig. 3), providing discrete states for the AURS control logic and the AURS guidance logic. The following points describe the implemented states:

a) UPSET_NONE: This state is set at the entry point or start of the state machine and indicates that no upset conditions are present.

b) UPSET_STAB: This state indicates a stabilized condition after the recovery process and contains a hysteresis function to avoid frequent changes between different states.

c) UPSET_STALL: This state will be entered if a stall event occurs. The current stall detection uses the angle-of-attack sensors to set the stall flag.

d) UPSET_HIGHSPEED: This state is present if maximum operating airspeed (V_{mo}/M_{Mo}) is exceeded.

e) UPSET_HIGH-/LOWPITCH: This state is present when the pitch-angle limitation is exceeded.

f) UPSET_HIGHBANK: This state is reached when the maximum bank angle is exceeded and can be reached from several other conditions. This state aims to reduce the load factor.

Based on the described states of the AURS strategy logic, the input parameters for the AURS control logic will be calculated. The input parameters contain pitch angle, bank angle, and thrust input. Rudder input was excluded during this development phase.

An AURS HMI guidance algorithm module controls the AURS guidance cues presented on the PFD, according to the strategy's steering commands. The AURS guidance laws continuously take into account the current operational envelope constraints, including load factor and airspeed constraints (stall speed V_{stall}, maximum operating airspeed V_{mo}, and maximum operating MACH M_{Mo}) throughout the automatic or manual-assisted upset-recovery maneuver.

B. Cockpit Integration

The AURS consists of a dedicated cockpit HMI to provide the required guidance cues as calculated by the AURS upset-recovery-strategy guidance logic. For the AURS concept evaluation, two proposed HMI configurations have been developed and experimentally assessed. All AURS guidance cues will be presented on the current PFD and integrated with the flight mode annunciator (FMA) to provide the AURS-mode status to the crew.

The first configuration (Fig. 4, left) consists of a conventional flight-director type of steering cues [upset flight director (UFD)], a sidestick-input-indicator cross, a graphical depiction of the current operational flight-envelope limits (envelope-limit box), and an FMA messaging protocol (recovery-mode annunciation). The envelope-limit box provides load factor and airspeed protection guidance, and continuously calculates the current load-factor limits and airspeed constraints (stall speed and maximum operating speed) during the upset maneuver. The dimension of the box, depicted by four white edges, is changed dynamically depending on the current aircraft limitations, and therefore, provides tactical information to prevent overstressing the aircraft, while following the AURS steering commands.

The UFD has been designed to allow the pilot to follow the correct upset-recovery steering actions, as calculated by the AURS strategy guidance logic. During an upset, the task of the pilot is to follow the AURS bars by approximately aligning the sidestick-input-indicator cross with the crossing of the bars. The AURS upset director bars are depicted in green to be consistent with the Airbus flight-director bars since the demonstrator was configured as an Airbus 320. Aircraft structural integrity and airspeed constraints during upset recovery are assured when the pilot aligns the sidestick-input indicator (cross)

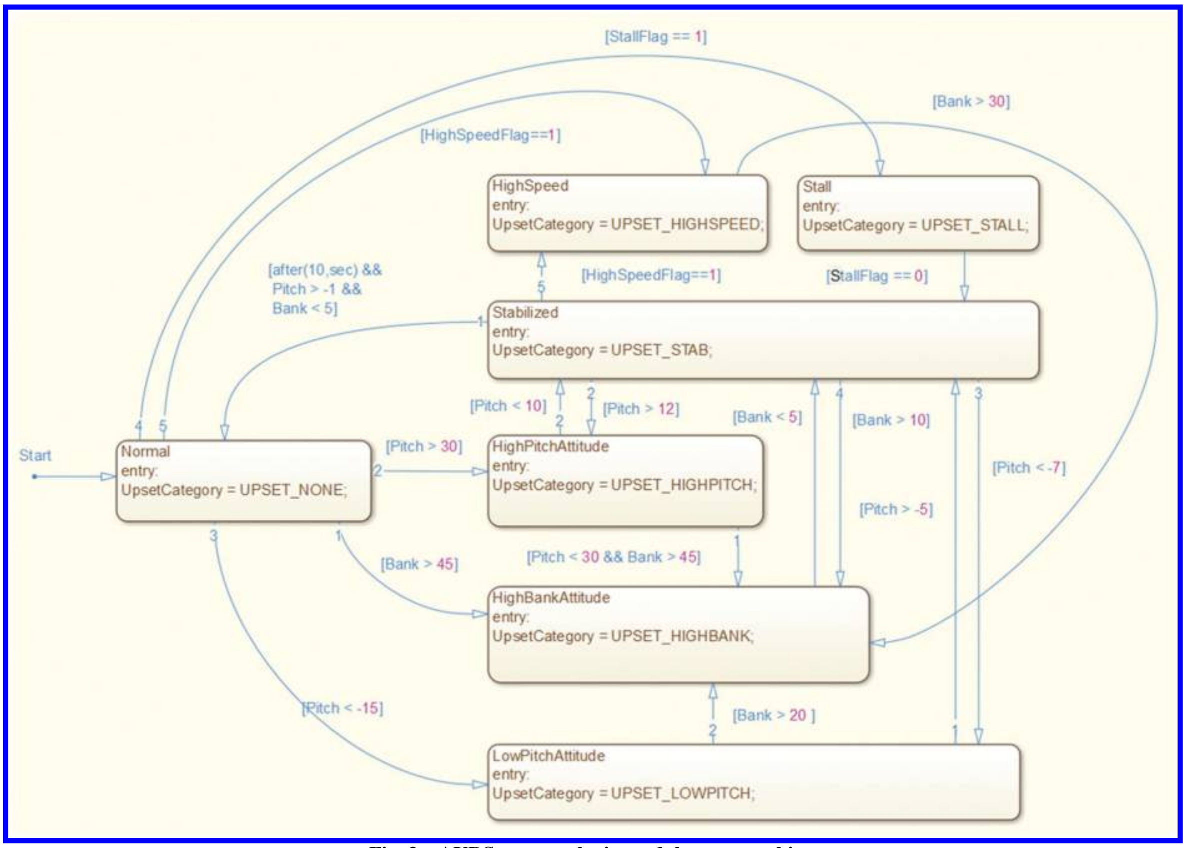

Fig. 3 AURS-strategy-logic-module state machine.

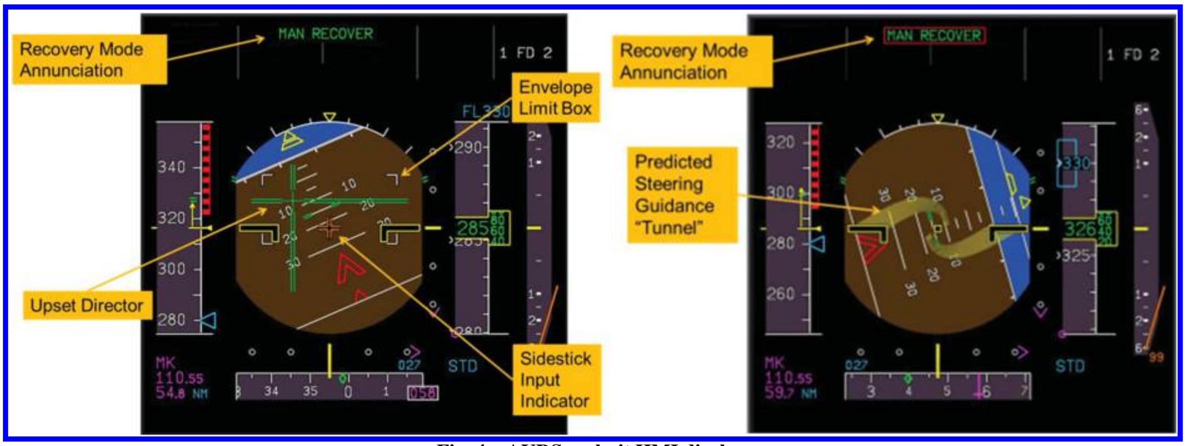

Fig. 4 AURS cockpit HMI display.

with the crossing of the UFD bars within the boundaries of the envelope-limit box. The sidestick-input indicator is color coded to provide cues on any excursions outside the envelope-limit box (white indicating correct recovery within the envelope-limit-box boundaries, amber when lagging behind correct steering commands, and red when outside the boundaries of the envelope-limit box). In this process, the AURS guidance laws calculate the compensatory actions depending on the pilot's control actions to prevent overcontrolling. The AURS-mode status is presented to the crew via the standard FMA. For certification, it is required that, during an upset, a minimum of information is presented to the crew to prevent mental overload. AURS intervention and mode annunciating will therefore cause all other current autoflight FMA modes to disappear except for the AURS-mode status. Depending on the AURS mode, the FMA will announce "man recover" in case the pilot is required to perform the upset recovery manually with AURS guidance cues, or "autorecover" when the system recovers from an upset in full automatic mode. Both the AURS FMA messages appear with red flashing boxes around them, indicating that the mode is active. These FMA messages will disappear again when the aircraft has been recovered within the normal operational flight envelope.

In the second AURS HMI cockpit-display configuration (Fig. 4, right), the UFD is replaced by a new graphical symbology aimed at providing better anticipatory steering cues (tunnel) during an upset recovery. The tunnel symbology (yellow marker) originates from the PFD wing markers on both sides, and extends forward toward the anticipated, or predicted, steering cues in the near future. The pilot's task is to continuously align both PFD wing markers with the predicted steering cues as provided by both ends of the yellow markers. During the recovery process, the yellow markers are deflected based on the AURS upset strategy logic. A point symmetric tunnel should lead to a roll maneuver, whereas a deflection toward a specific pitch angle should lead to a pitch maneuver. If the pilot follows the steering cues, the deflections of the yellow markers will decrease until they disappear behind the static wing markers when the upset situation has been solved. The commands are sequentially ordered to not overcharge the pilot in command. The FMA modes remain the same as for the AURS HMI UFD configuration.

C. Concept of Operation

For the AURS development and concept evaluation, the automatic and manual-assisted upset-recovery modes can either consist of the HMI UFD or tunnel-guidance cues. In this paper, the AURS concept of operation is demonstrated by showing an example of an AURS manual-recovery mode with the HMI UFD cues and an automatic-recovery mode with the AURS HMI tunnel symbology.

1. AURS Manual-Recovery Mode

Figure 5 shows the PFD layout and AURS guidance cues during a manual-assisted upset-recovery maneuver. Figure 5 (upper left) shows a nominal cruise condition at an altitude of 33,000 ft and at about 280 kt. The autopilot and autothrottle are engaged in Mach, altitude, and heading hold mode, as depicted on the FMA. An upset occurs (e.g., caused by extreme atmospheric effects or wake encounter), which causes the aircraft to fly outside the normal operational flight envelope into an unusual attitude condition. The autoflight system switches off, including the autoflight mode indications on the FMA. The AURS switches to the manual upset-recovery mode, as indicated by the FMA message, man recover (Fig. 5, upper right). An additional aural cue is provided to the pilot. In this phase, the AURS provides guidance cues to the pilot via the UFD bars (shown in green in the middle of the PFD), providing the steering commands for a correct recovery of the upset. The sidestick-input cross shows a white color, indicating that the control action of the pilot is adequately aligned with the AURS guidance cues, and within the load factor and airspeed constraint boundaries, as depicted by the envelope-limit box. Figure 5 (lower left) shows that the pilot's control inputs are violating the aircraft envelope constraints during the maneuver indicated by a red sidestick-input cross. As soon as the upset has been recovered within the normal flight envelope, the AURS UFD is removed from the PFD and autoflight guidance engages again, indicated by the FMA, to fly back toward the (preupset) altitude and speed, while stabilizing the aircraft further (AURS postexit guidance, in which control is handed over to the conventional autoflight system). Note that, during the maneuver, the aircraft remained in clean configuration. In this mode, thrust was manually applied by the pilot, as required, without guidance to prevent display cluttering.

2. AURS Automatic-Recovery Mode

The AURS automatic upset-recovery sequence, modes, and guidance cues are illustrated in Fig. 6. The flight starts again in cruise conditions at FL330 and at airspeed of about 280 kt (Fig. 6, upper left). As soon as the aircraft enters an upset condition, the AURS activates and disengages the autoflight system and indications. The automatic-recovery mode is engaged and indicated on the FMA by autorecover in addition to an aural cue (Fig. 6, upper right). The AURS tunnel guidance appears in the middle of the PFD (yellow) providing predicted (anticipatory) steering commands for a correct upset-recovery maneuver. In automatic mode, the tunnel provides cues of what the system tries to accomplish (Fig. 6, lower left). During the recovery phase, while the aircraft is still recovering from a low pitch attitude, and in some other conditions, the system allowed to slightly enter the red band of the PFD speed tape as a tradeoff to safely exit from the upset. When the automatic upset recovery is completed, the AURS tunnel guidance is removed and the autoflight system engages again in the postexit guidance, as shown on the FMA, to stabilize the aircraft further and steer toward the initial (preupset) speed and altitude (Fig. 6, lower right). In this mode, thrust was controlled automatically by the AURS.

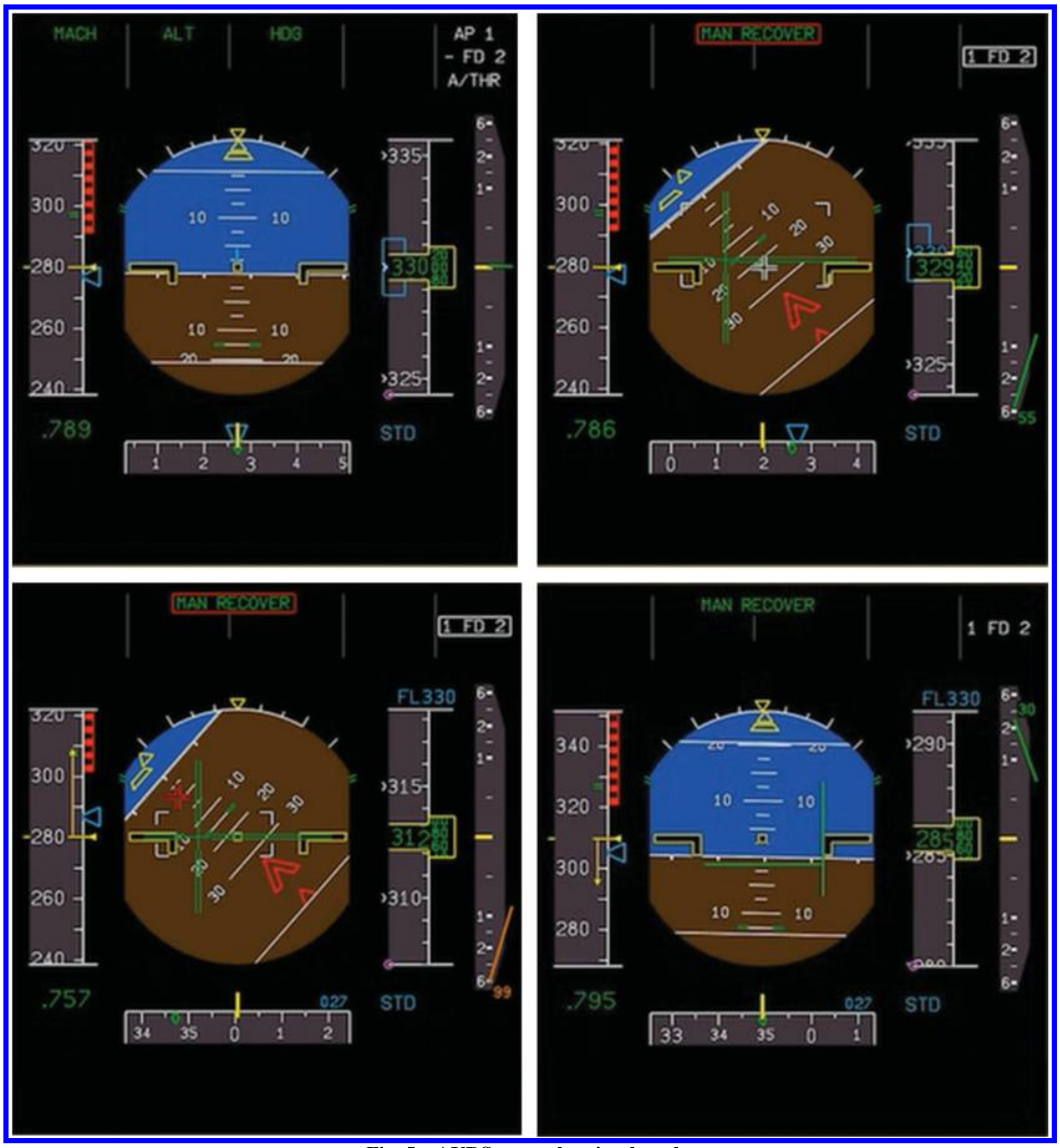

Fig. 5 AURS manual-assisted mode.

IV. Flight-Simulator Integration and Piloted Assessment

A. Objectives and Experiment Methods

The aim of the piloted evaluation was to assess the added value of both AURS manual and automatic-recovery strategies and HMI guidance in an operational environment, and how they relieve or assist the pilot in recovering the aircraft to the safe flight envelope following an upset. To achieve these objectives, the experiment applies the following evaluation methodologies:

1) Evaluation of the impact of manual-assisted upset recovery and automation functionalities and HMI aspects on pilot workload and situation awareness: to assess pilot workload and situation awareness, the NASA Task Load Index (TLX) (Appendix B) [20] and Crew Awareness Rating Scale (CARS) (Appendix C) [21] will be used.

2) Evaluation of HMI, and operational acceptability and usability of the automatic and manual-assisted-recovery strategies, including the AURS UFD and tunnel-guidance symbology: for this assessment, postrun and postexperiment questionnaires will be used, including acceptability rating scales and usability rating scales (Appendix C).

To assess the feasibility and potential benefits of the conceived AURS manual-assisted and automatic upset-recovery functionality, several preexperiment research questions were defined. The research questions were mapped into experiment hypotheses in the same numerical order that, for completeness, are listed in Appendix A.

B. AURS Technology Setups

Several AURS technology setups were prepared for the flight-simulator integration and piloted assessment of the different AURS configurations. The following AURS functionalities and system components were integrated in the real-time simulation environment: 1) AURS UFD, 2) AURS tunnel guidance, 3) AURS upset detection and recovery logic, and 4) AURS dedicated HMI with modified FMA to include manual or automatic upset-recovery modes.

Under all circumstances, the upset scenarios were triggered with the FCS in normal-law mode (Airbus type). The direct-law FCS mode was considered as an option, but, given the scope of the experiment, this was not taken into account. The combination of both manual-assisted and automatic-recovery operating modes of the AURS functionality resulted into the following five different HMI setups for the piloted assessment:

1) PFD with the UFD logic: in this setup, the pilot will fly and recover the aircraft manually using the AURS UFD guidance. This setup is referred to as the manual UFD (MAN-D) upset-recovery functionality.

2) PFD with the tunnel-guidance logic: in this setup, the upset recovery is performed manually with the aid of the AURS tunnel guidance. This setup is referred to as the manual tunnel (MAN-T) upset-recovery functionality.

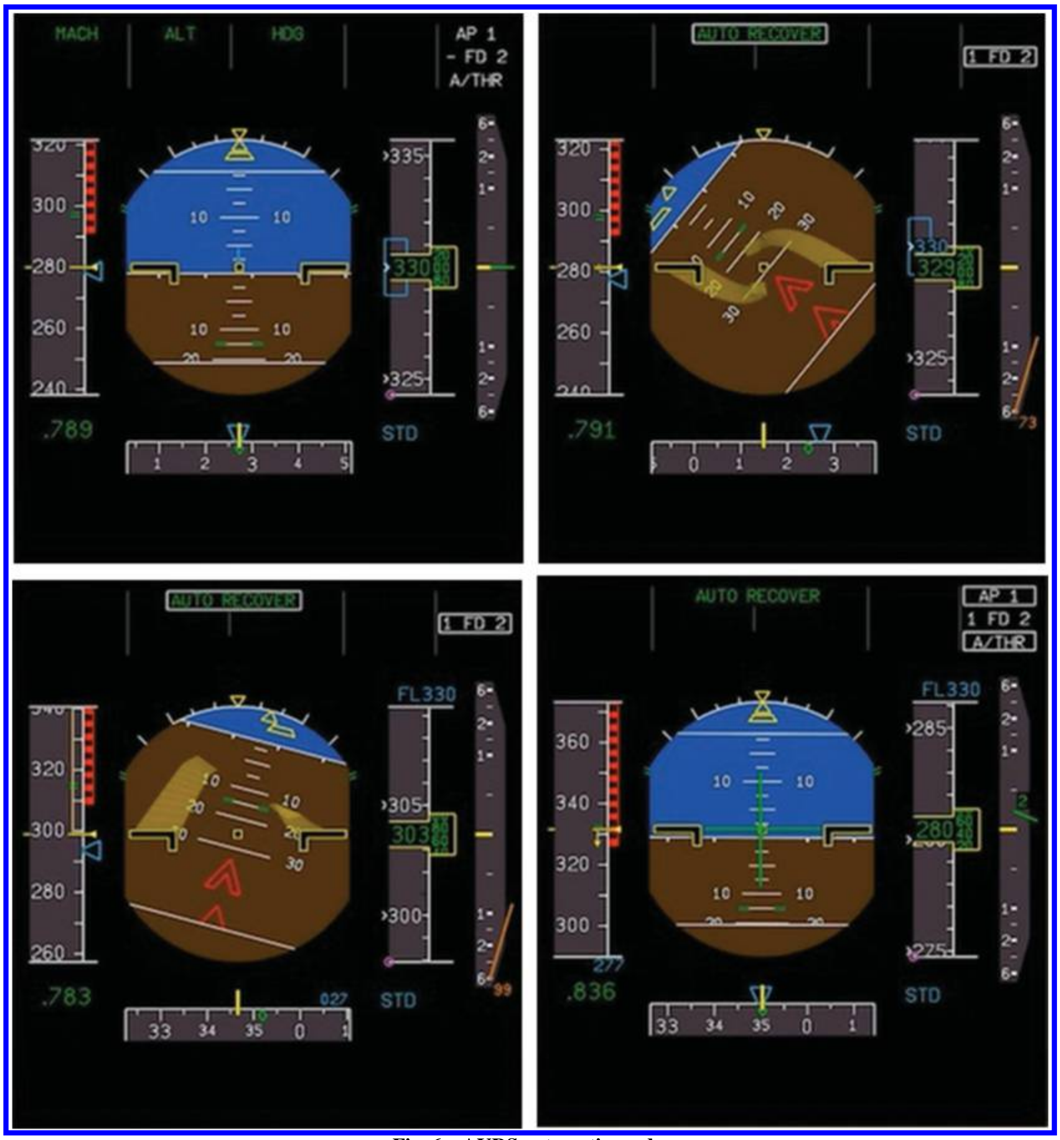

Fig. 6 AURS automatic mode.

3) PFD based on the automatic (AUTO) recovery functionality: in this setup, the upset recovery is performed fully automatically and the PFD only indicates a mode change on the FMA to indicate that the automatic-recovery mode is engaged. No other AURS HMI guidance cues are shown on the PFD during the recovery.

4) PFD based on the hybrid-recovery functionality consisting of the AURS automatic-recovery mode and UFD guidance (HYB-D): the PFD also shows the UFD guidance cues, but the recovery is executed fully automatically. No input from the pilot is required.

5) PFD based on the hybrid-recovery functionality consisting of the AURS automatic-recovery mode and tunnel guidance (HYB-T): the PFD also shows the tunnel-guidance cues, while the recovery is executed fully automatically. The pilot is not required to provide any inputs during the recovery.

Furthermore, a baseline existed that showed no special HMI, just the conventional PFD, and no support of the AURS during upsets (AURS OFF). This together constitutes an independent experiment variable with six levels.

C. Flight-Simulator Configuration

1. Flight-Deck Configuration

The Generic Research Aircraft Cockpit Environment (GRACE) is the Netherlands Aerospace Centre (NLR) transport cockpit research simulator facility that was used for the experiment (Fig. 7, left). The GRACE simulator features a two-seat flight deck typical of a transport aircraft. The standard instrumentation panel installed in the cockpit is equipped with large liquid-crystal displays that can be configured to represent the avionics systems of different aircraft types. For the experiment described in this paper, the flight deck was configured in Airbus A320-type layout (Fig. 7, right). The simulator's electronic control loading system comprised two Airbus-style sidesticks, pedals, and throttle station. The control loading model characteristics were configured to be representative of the A320 Airbus aircraft type.

The control of the experiment was performed via the GRACE control room (Fig. 8, left). The control room allowed to conduct the experiment, to manually activate the atmospheric-induced upset scenarios, and to monitor the AURS real-time system performance and pilot control actions though dedicated visualization tools (Fig. 8, right).

2. Motion System

The NLR GRACE simulator has an electrically driven hexapod motion platform delivered by Bosch Rexroth. Its performance capabilities are representative for today's commercially used motion platforms (Table 1). The motion-drive algorithms were not optimized for the goal of the experiment.

Fig. 7 NLR GRACE outside view (left) and AURS cockpit configuration (right).

Fig. 8 GRACE control room (left) and real-time aircraft upset-recovery visualization tools (right).

3. Visual System

GRACE is equipped with a wide-angle visual system using a three-channel collimated projection system giving a seamless image with field of view of about 180 deg horizontally and about 60 deg vertically.

4. Aircraft Configuration

The simulated aircraft was representative of an Airbus A320 type, including fly-by-wire FCS (Fig. 9). The experiment pilot was seated on the left side of the cockpit. All scenarios were flown in clean configuration (flaps and gear up) at a cruise altitude of 33,000 ft and at a speed of Mach 0.78 with the autopilot and autothrottle engaged at the start of each run. The flights were performed under instrument flight rules conditions. For this experiment, and due to time limitations, the cruise condition was chosen, as it is regarded as the most critical flight phase for any upsets in terms of load factor and speed safety margins within the aircraft operational and structural envelope. This condition also allowed the evaluation of the AURS load factor and speed-limitation function during upset recovery at high altitude. More flight conditions can provide other operational limitations (e.g., low-altitude flight), but these are considered for subsequent experiments in the future.

D. Participants

Ten professional pilots participated in the experiment. Each evaluation session was conducted by one pilot as pilot flying. It was preferable that the participants would have some experience flying Airbus-type aircraft, but this was not a prerequisite. A dedicated familiarization of the simulator cockpit, AURS functionalities, and standard upset-recovery techniques was given before the start of the actual measurements. Table 2 provides more details on the background and flight experience of the pilots who participated in the experiment.

Table 1 NLR's GRACE motion platform characteristics

Degree of freedom	Excursions	Acceleration	Velocity
Surge	660 [mm], −557 [mm]	±6.0 [m/s^2]	±0.855 [m/s]
Sway	553 [mm], −553 [mm]	±6.0 [m/s^2]	±0.855 [m/s]
Heave	446 [mm], −414 [mm]	±8.0 [m/s^2]	±0.611 [m/s]
Roll	17.75 [deg], −17.75 [deg]	±130.0 [deg/s^2]	±30.0 [deg/s]
Pitch	16.60 [deg], −17.25 [deg]	±130.0 [deg/s^2]	±30.0 [deg/s]
Yaw	22.05 [deg], −22.05 [deg]	±200.0 [deg/s^2]	±40.0 [deg/s]

Fig. 9 Airbus A320-type aircraft as used for the experiment.

E. Measures

1. Independent Variables

The upset detection and recovery functionality is regarded as the independent variable in this experiment. This variable is further divided into six levels comprising the different manual-assisted and automatic AURS configurations (Table 3).

2. Dependent Measures

The dependent measures of the experiment comprise the following elements: 1) pilots' rating of the workload, as measured by the NASA/TLX (postrun questionnaire); 2) pilots' rating of the situation awareness, as measured by the CARS (postrun questionnaire); and 3) acceptability and usability of the HMI, recovery logic, and recovery-logic performance, as measured in the postexperiment questionnaire.

The NASA/TLX ratings and CARS ratings are converted to z scores. If normality can be assumed, comparisons are made using parametric tests [e.g., t test and analysis of variance (ANOVA)]. If normality cannot be assumed, comparisons are made using

Table 2 Evaluation pilots

Pilot	Age	Gender	Flight hours	Test-pilot experience	Type ratings	Current rank
1	26	Male	1,000	No	B737, Cessna 205	First officer
2	30	Male	5,500	No	B777, Embraer 190	Captain
3	29	Male	3,850	No	B747-400, B737	First officer
4	38	Male	6,000	No	B737, Cessna Citation 650/550	First officer
5	38	Male	4,840	No	MD-11, CRJ 200/700/900	First officer
6	45	Male	14,000	No	B737 300/400/900, B747-400, A330	Captain
7	31	Male	1,200	No	A320	First officer
8	55	Male	15,818	No	DC10, B747, B737, MD-11, A330	Captain
9	63	Male	5,500	Yes	Fokker F50/70/100	Test pilot
10	36	Male	6,500	No	A330, Fokker F70/100, B747-400	First officer

Table 3 Independent variables

Recover mode/display	UFD	Tunnel	No display
Manual	Manual-D	Manual-T	— —
Automatic	Hybrid-D	Hybrid-T	— —
None	— —	— —	AURS off

nonparametric tests (e.g., Friedman's ANOVA). A hypothesis will be accepted if $p < 0.05$.

F. Test Scenarios and Procedures

Two aircraft upset scenarios (flight procedures) have been defined for the experiment (Table 4). For the upset scenarios, the initial flight parameters of the upset condition, as shown in Table 4, are introduced by an external disturbance caused by atmospheric effects (e.g., extreme turbulence or wake-vortex encounters [7]). The scenarios differ in terms of upset severity, in which the second scenario is the strongest upset. It should be noted that the scenarios were chosen to be as aggressive as possible to adequately excite the AURS, while the aircraft was initially flown in fly-by-wire normal law, to address the preliminary experiment aim of evaluating the cockpit HMI guidance features during upset recovery.

The experiment test matrix is shown in Table 5. Each session consisted of 12 runs, in which the AURS functionalities were tested for the two upset scenarios (flight procedures).

Table 4 Upset-scenario specifications

Flight procedure	Scenario description
1	En route, straight, and level flight with atmospheric disturbance resulting in a nose low (∼ − 10 deg) high bank (∼90 deg) attitude; left or right bank upsets will be introduced randomly
2	En route, straight, and level flight with atmospheric disturbance resulting in a nose low (∼ − 50 deg) high bank (∼135 deg) attitude; left or right bank upsets will be introduced randomly

Table 5 Experiment test matrix

Experiment run	Flight procedure	AURS functionality
1	1	OFF
2	1	MAN-D
3	1	MAN-T
4	1	AUTO
5	1	HYB-D
6	1	HYB-T
7	2	OFF
8	2	MAN-D
9	2	MAN-T
10	2	AUTO
11	2	HYB-D
12	2	HYB-T

1. Experiment Procedures

Before the start of the experiment (and after the pilot briefing was concluded), the pilots were able to familiarize themselves with the GRACE simulator, the new AURS basic functionalities, and upset-recovery techniques during a number of practice runs for about half an hour. After each experiment run, the pilot was asked to verbally summarize the essentials of that run (recorded on an audio track) and fill in a postrun questionnaire. The flight procedures and test cases, as provided by the test matrix, were offered in a random order to each of the pilots. At the end of the experiment, the pilots were asked to fill in a postexperiment questionnaire.

2. Flight Procedures

Before the start of each measurement run, the pilot was asked to close his eyes so that he was not aware of the type of upset to be introduced and to invoke a certain degree of surprise. After the simulator was put into operation, the operator initiated a particular upset between 10 and 20 s after operation. The pilot would only open his eyes at the moment when the aural alert "Upset, perform manual recovery" or "Upset, automatic recovery" was heard, and subsequently perform the upset recovery (when in manual-assisted mode) or monitor the recovery (when in automatic mode). The manual upset-recovery technique consisted of using roll control to obtain wings-level flight, while preventing stall and applying nose-up pitch to achieve stabilized level flight. Thrust would be applied as required to maintain speed limits. The pilot was instructed to not violate the aircraft operational limits (speed and load factor) during the maneuvers.

V. Results

This section presents and discusses the results of the AURS piloted-simulator campaign to address the evaluation objectives for the subjective assessment of the different AURS configurations and experimental setups, as described in Sec. IV. Objective measures were not part of the preliminary experiment aims. Based on the presented results, an assessment will be made in terms of the preference of the tested AURS configurations to reduce pilot workload, increase situation awareness, and allow safe interaction with the manual or automated upset-recovery system. Additional experimental findings will be discussed concerning the acceptability, usability, and the pilot's trust in using the automated upset-recovery functionalities.

Appendix A shows the experiment hypotheses and main test results obtained for all listed hypotheses of the AURS experiment. The results of all pilots were normalized into z scores. This transformation allows a higher comparability between the pilots. Depending on the distribution, the t test and Friedman ANOVA test types were used. The Lilliefors test was used to determine whether the results of a research question for a flight procedure (test scenario) were normally distributed. The normally distributed results were tested afterward with the t test and the nonnormal distributions with the nonparametric Friedman ANOVA test. Generally, a within-subject analysis was performed. The parametric ANOVA test could not be applied because the distributions did not meet the required homoscedasticity (equal variances). The research questions with crossed cells in Appendix A could not be tested with the used tests due to invalid data sets. The first column in Appendix A shows the hypothesis and its number. The second and third columns show the results for flight procedure 1 (FP-1) and flight procedure 2 (FP-2), respectively (Table 4). Whereas the *t* test or Friedman ANOVA test was used for the main hypothesis questions to determine whether the differences and improvements are statistically significant ($p < 0.05$), the subcategories were compared using the median and the upper and lower quartiles with a subjective valuation. Besides the median and quartile, the variance was considered to reveal diversities within the categories.

A. Workload Assessment

The NASA TLX ratings were used to evaluate the workload situation during the simulation runs for both upset scenarios (FP-1 and FP-2). The workload is divided into the categories mental demand, physical demand, temporal demand, performance, effort, and frustration. *Z* scores are used to normalize the ratings of each pilot.

Experiment hypothesis 1 (Appendix A) compares the baseline scenario without the AURS functionalities (OFF) with the manual-assisted recovery using the AURS UFD (MAN-D). The distribution of the workload categories for FP-1 (Fig. 10) shows a similar rating in each category. Only the category frustration shows a wider rating distribution for the baseline setup. For FP-2, the pilots stated less workload for the categories mental demand, physical demand, temporal demand, effort, and frustration. Besides the improved workload ratings, a high deviation in the category physical demand can be observed. The average of all categories underlines the mentioned workload improvement.

The different ratings between FP-1 and FP-2 may result from the fact that the upset occurring during FP-2 is more severe, and therefore, the AURS guidance display is used more than during a less severe upset.

In experiment hypothesis 2, the AURS tunnel guidance is being compared to the baseline setup (OFF). For FP-1, an improvement can be seen in every workload category (Fig. 11). The median and upper quartile values of the AURS MAN-T setup are lower than the baseline setup.

Similar to the previous experiment hypothesis, the differences between the baseline and the MAN-T setup are greater in FP-2 than in FP-1. This could lead to the assumption that the selected upset conditions require a higher demand on workload. Both setups dropped on the workload rating in FP-2, but there is a smaller gap using the MAN-T setup. More than 75% of all pilot ratings for the categories mental and physical demand show a lower workload situation during the MAN-T setup than during the baseline configuration. For the temporal demand and effort ratings, almost 75% of all pilot ratings tend to show less workload for the guided mode. For the remaining workload classifications, the box plot depicts a relative high deviation.

In hypothesis 6, the manual-assisted flight with the AURS UFD (MAN-D) and a fully automated recovery (AUTO) are being compared. In AUTO mode, the pilot only monitors the upset recovery, whereas in manual mode the pilot has to perform the recovery himself using the AURS UFD guidance cues.

In FP-1, the results show a clear improvement of workload reduction in terms of box-plot position and deviation (Fig. 12). As expected, the results show less workload during an automatic recovery as compared to the manual-performed recovery. The ratings

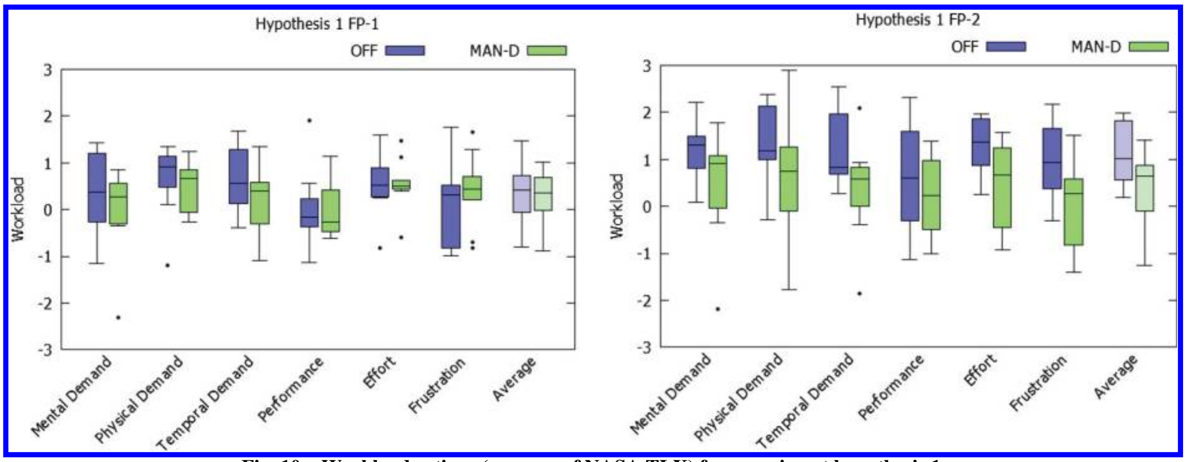

Fig. 10 Workload ratings (*z* scores of NASA TLX) for experiment hypothesis 1.

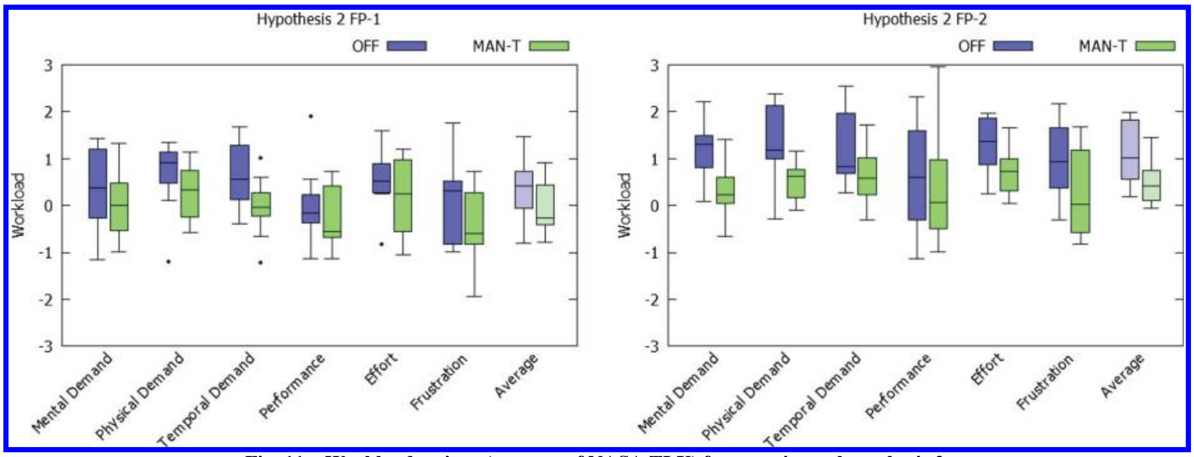

Fig. 11 Workload ratings (*z* scores of NASA TLX) for experiment hypothesis 2.

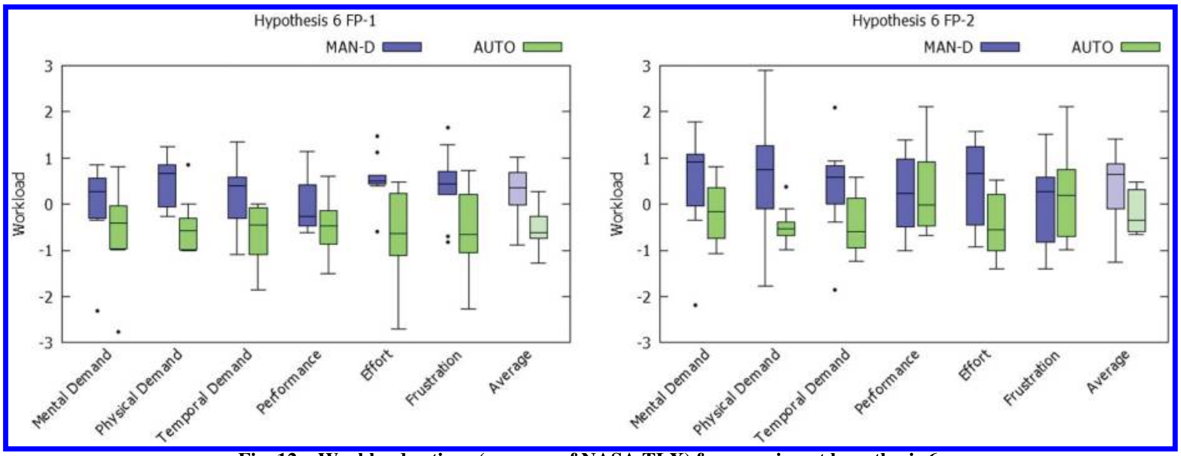

Fig. 12 Workload ratings (*z* scores of NASA TLX) for experiment hypothesis 6.

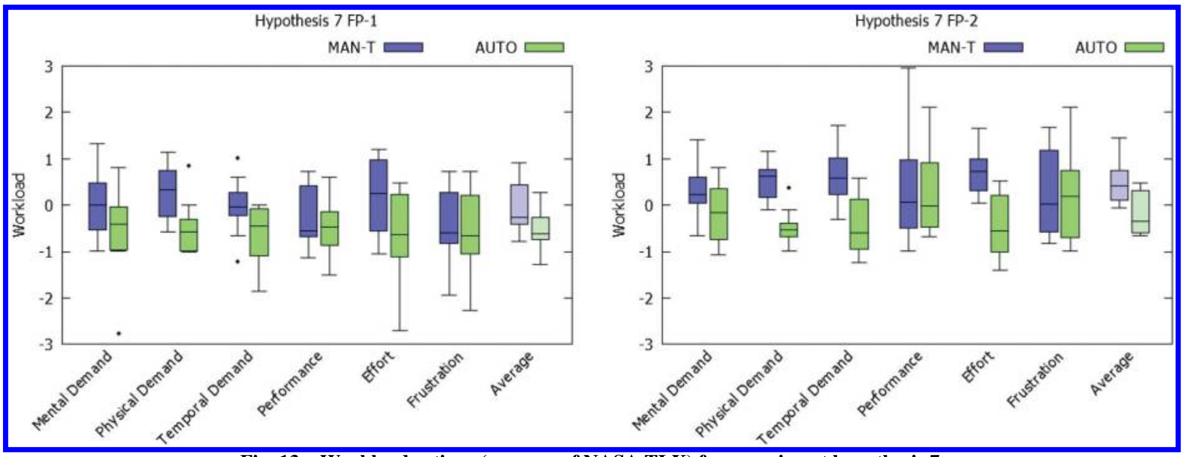

Fig. 13 Workload ratings (*z* scores of NASA TLX) for experiment hypothesis 7.

for FP-2 also show a reduction of workload using the AUTO setup. But, in this case, the differences are not as high as in FP-1, and the deviations are higher as well.

Hypothesis 7 considers the automatic recovery (AUTO) and the manual-performed recovery using the AURS tunnel guidance (MAN-T). In FP-1, the average results show a statistically significant improvement of workload reduction, as indicated by the box-plot position and deviation (Fig. 13). As also expected for this hypothesis, the results are showing less workload during an automatic recovery as compared to the manual-assisted recovery. Also, the ratings for FP-2 show a reduction of workload using the AUTO setup, but the differences are not as high as in FP-1, and the deviations are higher as well.

Hypothesis 12 compares two fully automated upset-recovery modes with each other. The first mode has no additional guidance elements (AUTO), whereas the second automatic mode provides the AURS UFD as a monitoring cue (HYB-D) during the recovery procedures.

FP-1 shows similar ratings for both modes (Fig. 14). There are some higher workload deviations noticeable for the physical and temporal demand categories using the HYB-D mode. The categories effort and frustration show a high deviation toward lower workload

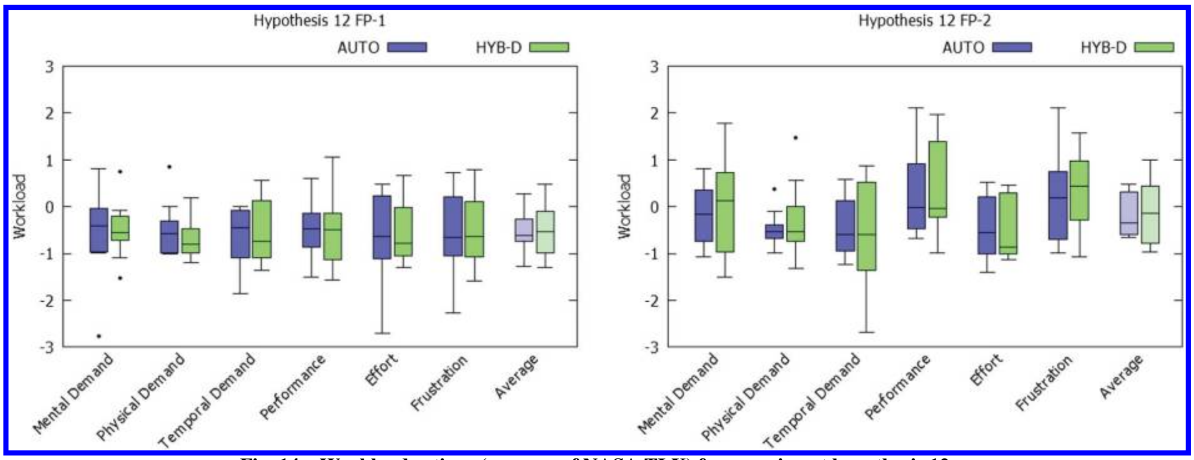

Fig. 14 Workload ratings (*z* scores of NASA TLX) for experiment hypothesis 12.

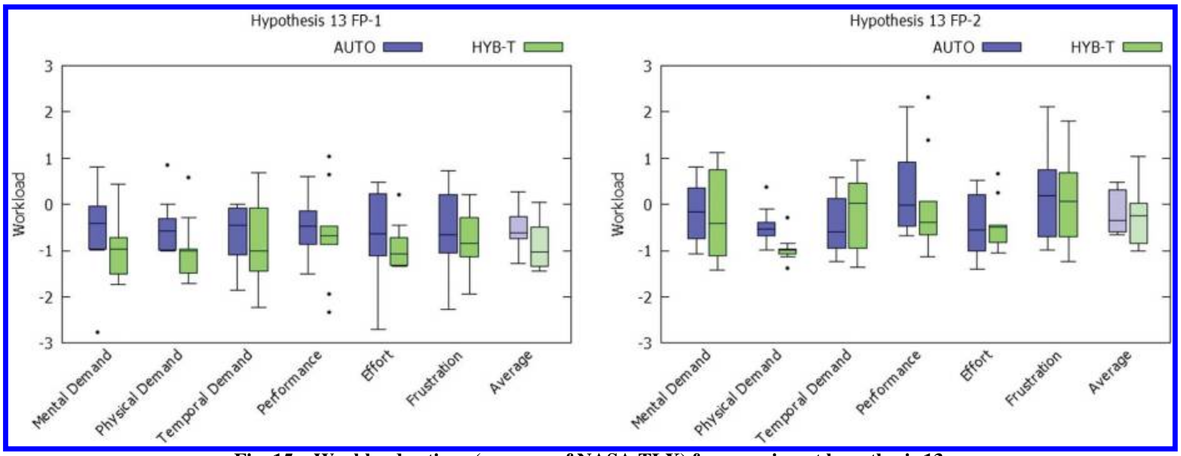

Fig. 15 Workload ratings (z scores of NASA TLX) for experiment hypothesis 13.

for the AUTO mode. In FP-2, the median values of the two automatic modes are at about the same level, except in mental demand, effort, and frustration. Even though the HYB-D effort rating shows some positive effect on workload, the median values of the mental demand and frustration ratings are less favorable. Despite the median values of these categories, there is a large distribution of the ratings, including their variances. The results indicate that there are no major improvements or disadvantages between the automatic modes.

Experiment hypothesis 13 is similar to hypothesis 12, except that, in this case, the AURS tunnel guidance was used as a monitoring cue during the automated recovery (HYB-T).

Unlike hypothesis 12, the differences are quite high between AUTO and HYB-T for FP-1 (Fig. 15). For this upset scenario, every median score of the HYB-T mode is rated with a lower workload than the median scores of the AUTO mode. For the mental demand, physical demand, performance, and effort categories, more than 75% of the pilot ratings show a lower workload using the HYB-T setup than the AUTO setup. FP-2 shows no mentionable difference between AUTO and HYB-T. Nevertheless, the pilots stated an improvement for FP-2 in the categories physical demand and performance.

B. Situation Awareness

The situation-awareness ratings given by the pilots after each experiment run were obtained using the questions as listed in the CARS (Appendix C).

For experiment hypothesis 3 (Fig. 16), the differences in FP-1 are not significant, except for the CARS question f, which shows some lower ratings for seeing the “big picture” using the AURS UFD during a manual recovery. But, the average rating still has a slightly better rating for the MAN-D mode compared to the baseline scenario (OFF). During the more severe upset (FP-2), the disparity between the modes gets more noticeable. There is a shift in the median score composed of CARS questions a, d, f, and h, although there is no evident difference.

The trend for FP-2 in hypothesis 3 can be transferred to hypothesis 4 (Fig. 17) comparing the baseline scenario (OFF) with the manual recovery using the AURS tunnel guidance (MAN-T). In general, there is an improvement in situation awareness recognizable for both upset scenarios in the MAN-T mode even though statistical significance could not be measured (Appendix A).

For FP-1, the pilots stated a higher situation awareness for CARS questions a, e, f, g, and h. Nevertheless, the average distribution is quite similar. Only the MAN-T median values tend to be higher than the OFF median values. In FP-2, the distributions are close to each other, which are underlined by the rejected hypothesis. Despite the rejected hypothesis, the median values and the surrounding $\pm 25\%$ of the ratings were better rated using the MAN-T configuration. (Question f appears to be the only exception.)

Comparing the autorecovery mode (AUTO) and the manual recovery using the AURS UFD (MAN-D) in FP-1 of hypothesis 8 (Fig. 18), the results show improved situation awareness for the manual mode in CARS questions c, d, and g. The pilots stated that they were more aware of how the situation was going to develop and that they could better foresee the goals using the AURS UFD than during the automatic recovery. However, the differences between AUTO and MAN-D are not significant.

In FP-2, the differences are evident. Every CARS question shows a shift of at least 50% of the z scores. That difference was tested as well using the t test. The probability of $p = 0.001$ underlines the significance of this hypothesis.

In hypothesis 9, the automatic recovery (AUTO) is compared to the manual recovery using the AURS tunnel guidance (MAN-T) (Fig. 19). Corresponding to hypothesis 8, there is an improvement of situation awareness in every category. In FP-1, the differences are not significant ($p = 0.07$), but there is a shift of about 20–50% of the ratings depending on the CARS question. In contrast to FP-1, the

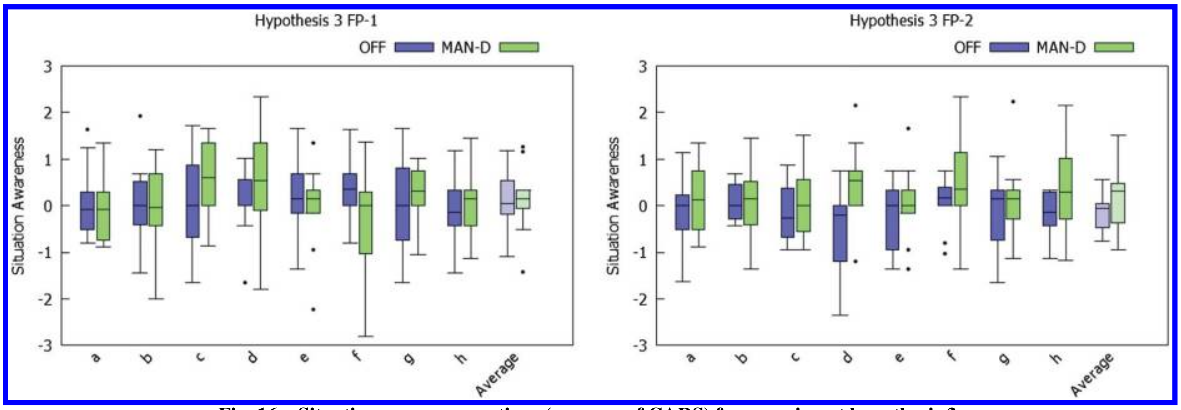

Fig. 16 Situation-awareness ratings (z scores of CARS) for experiment hypothesis 3.

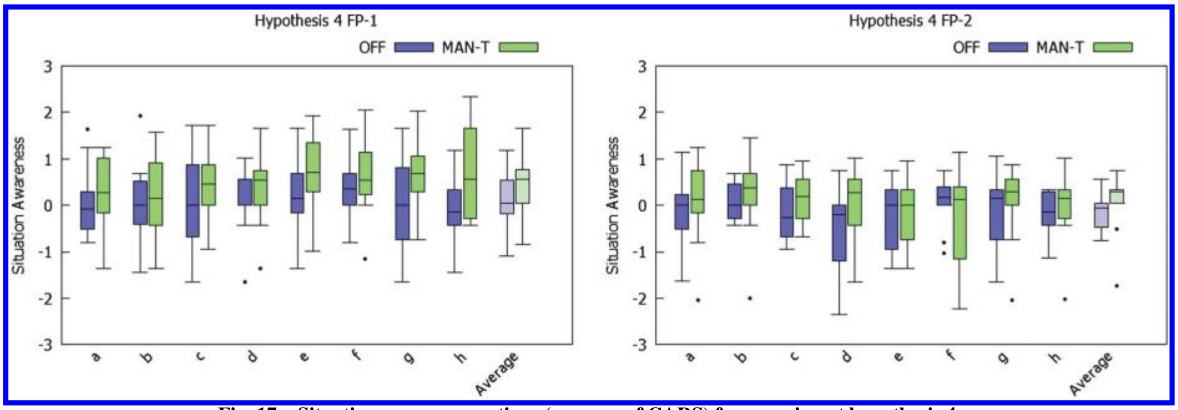

Fig. 17 Situation-awareness ratings (z scores of CARS) for experiment hypothesis 4.

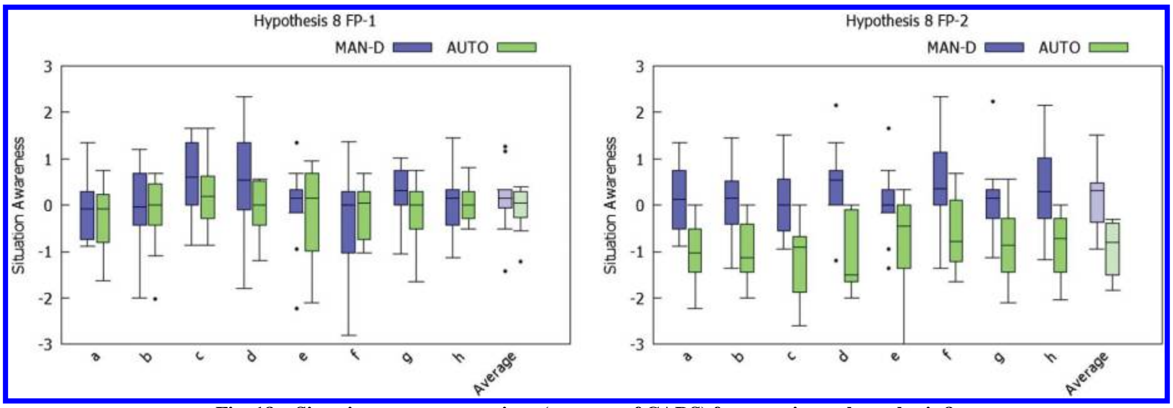

Fig. 18 Situation-awareness ratings (z scores of CARS) for experiment hypothesis 8.

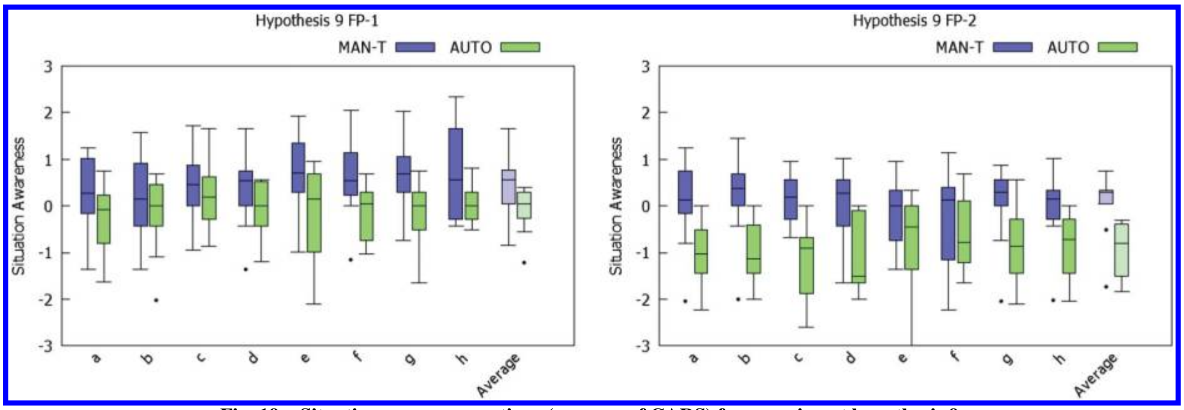

Fig. 19 Situation-awareness ratings (z scores of CARS) for experiment hypothesis 9.

results of FP-2 show a significant improvement using the AURS tunnel guidance. The Friedman ANOVA test results in a probability of $p = 0.006$ showing the significance.

Comparing the fully automatic-recovery mode (AUTO) with the automatic hybrid mode using the AURS UFD (HYB-D) (hypothesis 14, Fig. 20), there is no significance detectable in both upset scenarios. The average rating for FP-1 is a result of the scores in CARS questions a, d, f, g, and h. FP-2 shows slightly better results (FP-1: $p = 0.149$; FP-2: $p = 0.075$), but the variances are quite high. Therefore, there is no significant difference in situation awareness between the AUTO and HYB-D modes.

Hypothesis 15 deals with the comparison between the autorecovery (AUTO) and the automatic recovery using the AURS tunnel-guidance cues (HYB-T) (Fig. 21). The z scores of FP-1 show more similarities than the scores of the more severe upset in FP-2. In FP-2, every CARS question for the HYB-T mode is rated higher, which results into a probability p of less than 0.001.

C. Automation Trust, Usability, and Acceptability

The level of trust in the AURS automated functions was assessed using hypotheses 10, 11, 16, and 17 (Appendix A). Automation trust, and operational acceptability and usability of the AURS functionalities were evaluated using the questionnaires, as shown in Appendix C.

The experiment results show that the level of the pilot's trust in the AURS automated functions for upset recovery increases for both upset scenarios when the automatic-recovery function was supplemented with the AURS HMI guidance cues (hybrid-recovery functionalities) compared to the automatic-recovery function without any HMI guidance (hypotheses 10 and 11). The level of automation trust also increases for both upset cases when the automatic-recovery function was used instead of the manual-assisted-recovery functions with HMI guidance cues (hypotheses 16 and 17).

The AURS functionalities and HMI presented little opportunity for human error. The manual and automatic recoveries (and associated

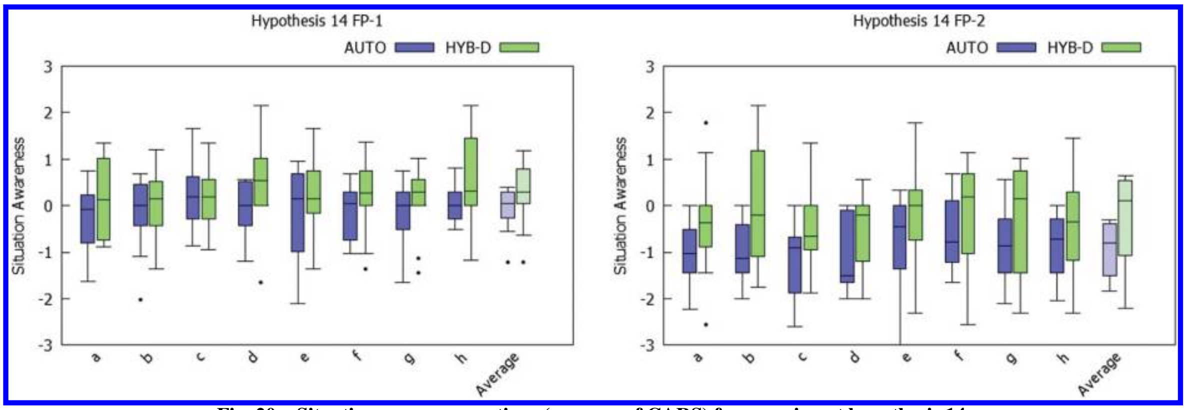

Fig. 20 Situation-awareness ratings (z scores of CARS) for experiment hypothesis 14.

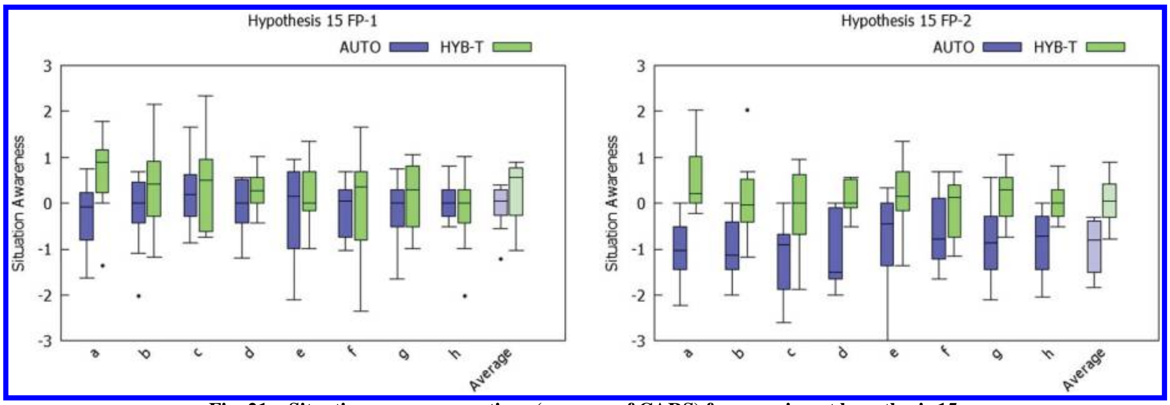

Fig. 21 Situation-awareness ratings (z scores of CARS) for experiment hypothesis 15.

HMI and logic) were found rather straightforward by the pilots. From an operational standpoint, several issues were raised and commented by the evaluation pilots. The AURS tunnel-guidance cue was found to be more intuitive by some pilots, which probably explains the lesser NASA TLX frustration level. In general, the AURS tunnel guidance appears more favorable as compared to the AURS UFD. In a fully automated recovery, it seems that the AURS tunnel-guidance cue enables to adequately inform the pilot of the upset situation and aircraft state. In particular, pilots commented that, during an automatic recovery following a severe upset, they felt the need for feedback on how the automatic system will correct the upset, what it tries to accomplish, and its steering actions. However, the use of a conventional flight director as a guidance cue for (automatic) upset recovery might be preferable from an operational viewpoint due to the rareness of upset events. Pilots noted that a conventional flight director as a guidance cue is felt more familiar when in a highly stressful rare upset event. It was further observed that additional features, like the AURS envelope-limit box, giving real-time indication on the operational limitations of the aircraft during an upset, were not monitored when initially recovering from an upset manually. In general, the pilots noted that the AURS automatic functionalities reduced workload, while increasing their ability to observe and assess the situation.

D. Summary

The piloted-simulator evaluation of the AURS showed that the functionalities of the system are able to support pilots during an upset. Even if pilots are trained for an upset event, most pilots can get (mentally) overloaded when an upset actually occurs during operation. The experiment showed that pilots are willing to rely on the guidance provided by the AURS during an upset. Thereby, it is important for pilots to see and understand what the aircraft is doing and trying to do especially in automatic modes.

Comparing the manual-assisted and automatic-recovery modes, the pilot's opinion was that an automatic recovery reduces the workload so that they could perform a proper screening of the PFD. The results further show that the two manual-assisted recoveries, with AURS guidance cues, reduced workload for the most severe upsets only compared to today's situation. When comparing the AURS automatic control functions, the workload was reduced compared to the manual interfaces. The hybrid AURS UFD functionality, in contrast to the hybrid AURS tunnel guidance during a moderate upset, did not decrease the workload compared to the automatic AURS function. Figure 22 shows an overview of the ratings regarding the workload combining both upset scenarios. The automatic modes have the highest impact on workload reduction. Figure 22 also shows that the AURS tunnel guidance has slightly better workload ratings than the AURS UFD. It is believed that better tuning of the AURS UFD might improve the effect on workload.

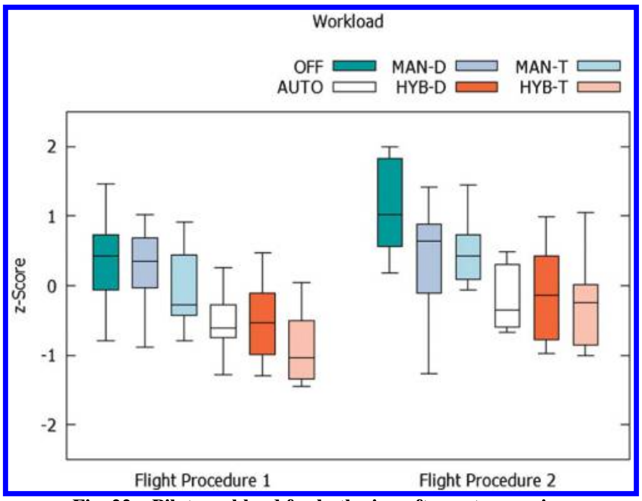

Fig. 22 Pilot workload for both aircraft upset scenarios.

The level of situation awareness was improved for both hybrid AURS systems compared to the automatic-recovery modes without guidance. An improvement in situation awareness was noticeable with the manual-assisted AURS functionalities as compared to the nonassisted-recovery procedure. The current AURS concept does not allow overruling the automatic upset detection and recovery action, but it is expected that a future system would have an option to allow the pilot to take over the control of the aircraft at any time.

VI. Conclusions

An (semi) automatic aircraft upset-recovery system (AURS) was developed and evaluated by means of a piloted-simulator experiment. To mitigate the highly physical and psychological impact during aircraft upset events, the AURS provides new cockpit functionalities to support the pilot in recovering from any upset both manually assisted and automatically.

The piloted-simulator evaluation of the AURS showed that workload was significantly reduced for both manual-assisted and automatic control modes compared to today's situation, in which no guidance is provided for upset recovery. In particular, pilot workload was lower for the automated upset recovery, while information was displayed on the automation status. The pilot's trust in the new functionalities was higher for the automated versions of the AURS that showed visual-guidance cues via the primary flight display (PFD) human–machine interface (HMI). This configuration provided the pilots with better feedback of the operation of the system during upset recoveries. Also, the AURS was found rather straightforward to use, although some areas of improvement were identified. From a flight-operational-safety viewpoint, the introduction of the developed solutions is likely to positively impact the operational safety by means of reduced workload and improved situation awareness.

Further research and development of the AURS concept, which achieved a technology readiness level of 5 in this study by means of real-time piloted assessment, is foreseen. In the case that one or more aircraft subsystems fail, guidance cues should be calculated and displayed especially in cases, in which the current aircraft flight state cannot be assessed accurately. This becomes important if, for instance, the aircraft's flight-envelope protection cannot be provided anymore and backup flight-state information needs to be extracted. In such cases, the accuracy and reliability of calculated flight states degrade, and research is needed to provide upset detection and recovery algorithms that can process this degraded information. It is further foreseen to enhance the AURS HMI to be integrated into future PFDs, which are depicted on large displays that may include enhanced or synthetic vision, or a combination of these. The AURS automatic modes have the highest impact on workload reduction, situation awareness, and stress reduction; thus, future developments for upset-recovery guidance and loss-of-control prevention should focus on automatic-recovery solutions.

Appendix A: AURS Experiment Hypotheses and Test Results

Hypothesis (H)	Flight scenario 1	Flight scenario 2
1. The upset detection and Manual-D upset recovery reduces workload compared to the non-assisted standard recovery procedure.	Test: t-test p: 0.754 H: rejected	Test: t-test p: 0.035 H: **accepted**
2. The upset detection and Manual-T upset recovery reduces workload compared to the non-assisted standard recovery procedure.	Test: t-test p: 0.134 H: rejected	Test: t-test p: 0.019 H: **accepted**
3. The upset detection and Manual-D upset recovery increases Situation Awareness compared to the non-assisted standard recovery procedure.	Test: t-test p: 0.888 H: rejected	Test: t-test p: 0.1637 H: rejected
4. The upset detection and Manual-T upset recovery increases Situation Awareness compared to the non-assisted standard recovery procedure.	Test: t-test p: 0.204 H: rejected	Test: Friedman p: 0.221 H: rejected
5. The flight is recovered within acceptable performance criteria (acceptable period of time, acceptable altitude loss, acceptable oscillations and within V,n envelope) in Hybrid-D, Hybrid-T and Automatic functionality. In Manual-D and Manual-T recovery and during non-assisted standard recovery, the performance may be acceptable or unacceptable.	Test: t-test p: H:	Test: t-test p: H:
6. The upset detection and Automatic recovery functionality reduces workload compared to the Manual-D upset recovery procedure.	Test: t-test p: 0.002 H: **accepted**	Test: t-test p: 0.094 H: rejected

7. The upset detection and Automatic recovery functionality reduces workload compared to the Manual-T upset recovery procedure.	Test: t-test p: 0.044 H: **accepted**	Test: t-test p: 0.008 H: **accepted**
8. The upset detection and manual-D recovery functionality increases Situation Awareness compared to the automatic upset recovery procedure.	Test: Friedman p: 0.724 H: rejected	Test: t-test p: 0.001 H: **accepted**
9. The upset detection and manual-T recovery functionality increases Situation Awareness compared to the automatic upset recovery procedure.	Test: Friedman p: 0.077 H: rejected	Test: Friedman p: 0.006 H: **accepted**
10. The automation trust increases when the Hybrid-D recovery functionality is used compared to the Automatic recovery functionality	Test: t-test p: < 0.001 H: **accepted**	Test: Friedman p: 0.002 H: **accepted**
11. The automation trust increases when the hybrid-T recovery functionality is used compared to the automatic recovery functionality.	Test: t-test p: < 0.001 H: **accepted**	Test: t-test p: < 0.001 H: **accepted**
12. The upset detection and Hybrid-D recovery functionality decreases workload compared to the Automatic recovery functionality.	Test: t-test p: 0.9345 H: rejected	Test: t-test p: 0.8877 H: rejected
13. The upset detection and Hybrid-T recovery functionality decreases workload compared to the Automatic recovery functionality.	Test: t-test p: 0.178 H: rejected	Test: t-test p: 0.631 H: rejected
14. The upset detection and Hybrid-D recovery functionality might increase Situation Awareness compared to the Automatic recovery functionality.	Test: Friedman p: 0.149 H: rejected	Test: t-test p: 0.075 H: rejected
15. The upset detection and Hybrid-T recovery functionality increases Situation Awareness compared to the Automatic recovery functionality.	Test: Friedman p: 0.166 H: rejected	Test: t-test p: < 0.001 H: **accepted**
16. The automation trust increases when the Automatic recovery functionality is used compared to the Manual-D recovery functionality.	Test: t-test p: < 0.001 H: **accepted**	Test: t-test p: < 0.001 H: **accepted**
17. The automation trust increases when the Automatic recovery functionality is used compared to the Manual-T recovery functionality.	Test: t-test p: < 0.001 H: **accepted**	Test: t-test p: < 0.001 H: **accepted**
18. The HMI 'upset director' is acceptable to pilots.	Test: t-test p: H:	Test: t-test p: H:
19. The HMI 'upset tunnel' is acceptable to pilots.	Test: t-test p: H:	Test: t-test p: H:
20. The recovery logic (in Manual-D, Manual-T, Hybrid-D, Hybrid-T and Automatic functionality) is acceptable to pilots.	Test: t-test p: H:	Test: t-test p: H:

Appendix B: NASA TLX Rating Scale

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed were you?

Very Low — Very High

Appendix C: CARS, Acceptability, and Usability Rating Scales

Situation Awareness Rating: Please indicate how you experienced the last run on average

a. Would you say your awareness of relevant information is satisfactory?

Definitely negative	Probably negative	Probably positive	Definitely positive
☐	☐	☐	☐

b. Would you say your grasp of the situation—i.e., understanding of what is going on—is satisfactory?

Definitely negative	Probably negative	Probably positive	Definitely positive
☐	☐	☐	☐

c. Would you say your awareness of how the situation is likely to develop over time is satisfactory?

Definitely negative	Probably negative	Probably positive	Definitely positive
☐	☐	☐	☐

d. Would you say your awareness of how best to achieve your goals is satisfactory?

Definitely negative	Probably negative	Probably positive	Definitely positive
☐	☐	☐	☐

e. Would you say it is easy to keep up to speed with the details of the situation?

Definitely negative	Probably negative	Probably positive	Definitely positive
☐	☐	☐	☐

f. Would you say it is easy to make sense of the situation as a whole, to see the "big picture"?

Definitely negative	Probably negative	Probably positive	Definitely positive
☐	☐	☐	☐

g. Would you say it is easy to foresee or predict the likely progress or events?

Definitely negative	Probably negative	Probably positive	Definitely positive
☐	☐	☐	☐

h. Would you say it is easy to decide upon the best course of action?

Definitely negative	Probably negative	Probably positive	Definitely positive
☐	☐	☐	☐

Acceptability

a. The information on the PFD was useful

☐ Completely disagree	☐	☐	☐	☐ Completely agree

b. The information presented on the PFD was easy to use

☐ Completely disagree	☐	☐	☐	☐ Completely agree

c. I trusted the information presented on the PFD

☐ Completely disagree	☐	☐	☐	☐ Completely agree

d. I trusted the recovery automation

☐ Not applicable

☐ Completely disagree	☐	☐	☐	☐ Completely agree

e. The upset was recovered within acceptable limits

☐ Completely disagree	☐	☐	☐	☐ Completely agree

Usability

a. The information on the PFD supported me in the task effectively

☐ Completely disagree	☐	☐	☐	☐ Completely agree

b. The information on the PFD supported me in the task efficiently

☐ Completely disagree	☐	☐	☐	☐ Completely agree

c. I was satisfied with the available information on the PFD

☐ Completely disagree	☐	☐	☐	☐ Completely agree

d. Were there any difficulties in using the information on the PFD? If yes, please specify.

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