

# ELECTRONIC COUPLED ACTIVE SIDESTICKS IN DUAL PILOT HELICOPTERS FOR INSTRUCTIONAL FLIGHTS

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## Abstract

Notably in training flights, mechanical linkages between pilot's and copilot's controls are crucial to the pilot's situation awareness and to takeover control maneuvers. However, in near-obstacle helicopter scenarios, the control transfer between pilots can lead to loss-of-control accident caused by interaction on inceptors, as safety reports indicate. As an alternative to mechanical linkages, the electronic cross-cockpit control coupling is introduced as a smart flight control system to actively decouple inceptors, and thus to mitigate this category of accidents. The paper proposes a novel methodology to evaluate the suitability of the Electronic Coupled Active Sidesticks to helicopter domain, particularly applied to training flights. Results point to the ability of the electronic coupling to effectively emulate the mechanical linkage between control stations and perform full interventions on the 'linked' mode. Moreover, test pilots rated the system capable to decouple controls either by priority override pushbutton (manual) or by priority algorithm based on the logics of pilot activities (automatic force threshold).

## ABBREVIATIONS

AIS	Active Inceptor System
ARP	Aerospace Recommended Practice
CFI	Certificated Flight Instructor
EC-AIS	Electronic Coupling of AIS
EP	Experimental Pilot
FBW	Fly-By-Wire
FCCMC	Flight Control Mechanical Characteristics
FCC	Flight Control Computer
FCS	Flight Control System
FHS	Flying Helicopter Simulator
FOV	Field of View
FT	Force Threshold
LOC	Loss of Control
PF	Pilot Flying
PFD	Primary Flight Display
PM	Pilot Monitoring
RQMT	Requirement
SA	Situation Awareness
SAGAT	Situation Awareness Global Assessment Technique
TP	Test point
2PASD	Dual Pilot Active Sidestick Demonstrator

## 1. INTRODUCTION

The electronic connection between pilot's and copilot's controls is introduced as an alternative to the traditional mechanical linkage. It can be achieved through the Active Inceptor System (AIS), a class of pilot controllers that uses high bandwidth actuation to generate the force-displacement characteristics in real time and thereby provide augmented control (Fig. 1). The terminology "inceptor" indicates any device that is used to provide pilot control inputs.

In the 'linked' operation, both pilots can monitor inputs through the tactile feedback, which is helpful to eliminate confusion between pilots [1].

The cross-cockpit control coupling is a channel of communication between the pilots and an important part of cockpit error management. It can provide intuitive and continuous feedback to the pilots to help them understand the risks involved in a given flight situation. In high demanding and time-critical conditions, the tactile information stimulates fast reflexive motor responses, since it does not influence mental workload required to visual monitoring [2]. Thus, it aids the pilots to identify a condition where can be necessary to take over control of the aircraft, particularly in high workload situation.

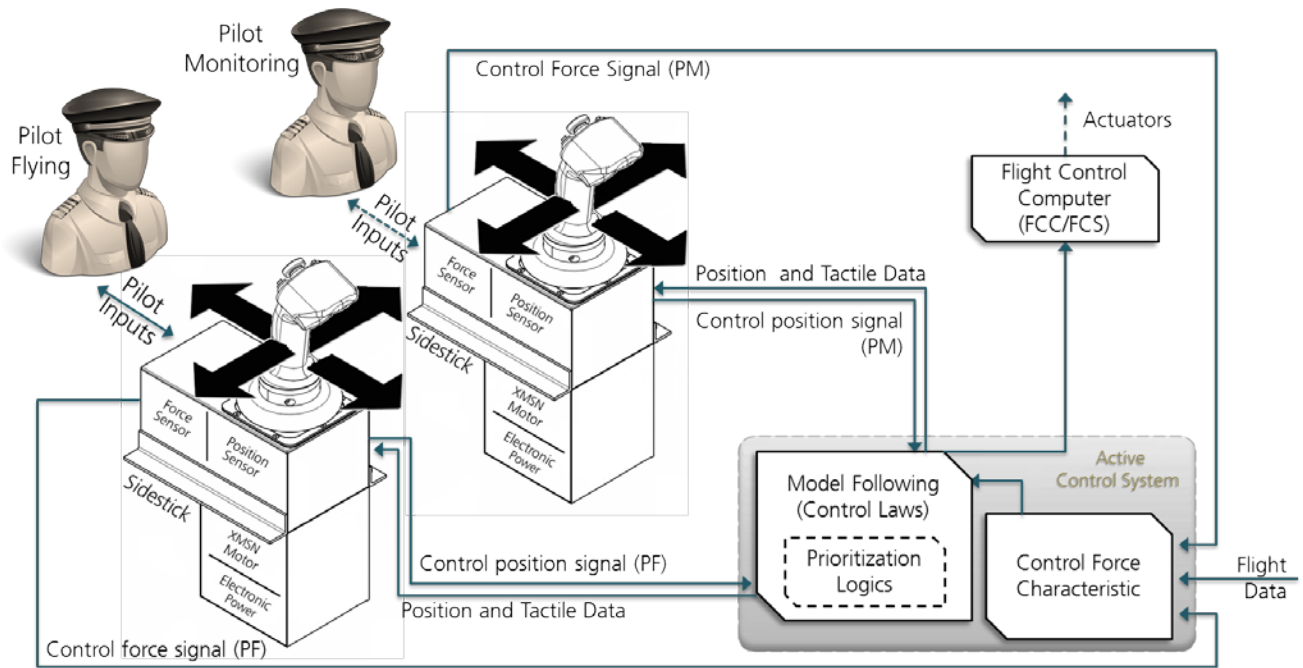


Fig. 1 – Electronic Coupling of Sidesticks through Active Control System.

The action of taking control is the standard behavior of the crew during unforeseen or unsafe conditions [3]. Inadequate time for verbal interactions can occur and an inevitable manual control overriding must be immediately assessed, even without prior notice. It brings about cases of simultaneous inputs from both pilots on the same inceptor type. In these cases, the coupling of AIS is an important feature to crew perception that the both pilots are trying to control the helicopter at the same time.

These aspects have a meaningful impact on training flights, particularly for helicopters. Based on the current mechanical linkages of conventional controls, accident reports indicate the interference with controls as the second most frequent contributing factor to loss of control (LOC) accidents in helicopter instructional flights [4]. These events include a recurrent type of accident in training caused by lack of positive transfer of controls between pilots, even when the instructor acted timely [5]. Moreover, most of these accidents occurred when an experience certificated flight instructor (CFI) was in the cockpit [6]. Thus, a smart flight control system to actively vary the inceptor linking status could be addressed to mitigate this category of accidents and to increase the helicopter safety.

However, there remains lack of evidence on the consequences of these active functions to the

helicopter scenarios, like near obstacle environment. Existing investigations of electronic coupled active inceptors are geared towards the demands of dual-pilot aircrafts. Summers et al. [7] and Uehara [8] explored the consequences of takeover maneuvers through comparison between active coupled and passive uncoupled sidesticks. The first investigation concluded that pilots preferred the coupled configuration, because the force feedback through the control stick communicated a sense of urgency. The second study indicates that the coupling is useful to perceive the other pilot control inputs and to the decision of taking over control. It should be noted that no control disengagement was evaluated in the active couple configurations. Thus, the systematic understanding of the most appropriate design to actively couple and decouple the flight controls in the helicopter realm has not been established.

### 1.1. Scope of Study

This study aims to propose a novel methodology to evaluate the suitability of the Electronic Coupling of AIS, namely EC-AIS, to helicopter domain, particularly applied to training flights.

The EC-AIS can be disconnected according to the user needs, either by priority pushbutton (manually) or by priority algorithm based on the logics of pilot activities (automatically). Additionally, the active

function to recouple the controls can be immediately available for both pilots.

The new approach scrutinizes the influence of active functions on controllability and helicopter flight safety. The method is divided in the following five steps (Fig. 2):

1. AIS Nominal Settings: define the system design, specifically the nominal FCMC (Flight Control Mechanical Characteristics);
2. Situation Awareness test: highlight the weakness and strengths of the electronic couple active system in 'linked' mode. The assessment has the potential to apply design modifications in early development phases;
3. Virtual Rigid Electronic Coupling: evaluate the ability of the electronic coupling to emulate the mechanical linkage between control stations ('linked' mode);
4. Electronic Decoupling: examine the capability to decouple controls manual and automatically. Herein, the logics and system protection against failures are verified in extensive conditions for both pilot cabins;
5. Analysis of Transients: investigate the feasibility to couple and decouple controls gradually without causing sudden transients, either before a coupling or after a decoupling.

## 2. SIMULATION SETUP

Investigations were conducted in a ground-based helicopter simulator for dual pilot cockpit (Fig. 3) featuring coupled active sidesticks at the Institute of Flight Systems of the DLR.

The simulation platform, "2 Pilot Active Sidestick Demonstrator" (2PASD), operates in pseudo real-time MATLAB/Simulink environment. The helicopter model is an augmented full-envelope simulation model of the ACT/FHS [9-10], a highly modified EC-135. For this reason, its performance and qualities do not reflect operational variants of the rotorcraft type.

The simulation platform is a laboratory environment to prototype active inceptor functions and to validate pilot assistance systems in early stages of design. It provides the ability to conduct extensive evaluations for two control stations for a multi crew rotorcraft operation.

Due to the modular concept, the cockpit construction allows the conversion of different seat arrangements (Side-By-Side and Tandem). The facility can be customized to different ergonomics configurations and anthropometric sizes, due to the extensive position options of the seat, pedals and monitors. The reference values for the seat and the armrest is based on DLR's Air vehicle Simulator (AVES) simulator [12], which contains a replica of the EC135 ACT/FHS cockpit. The mounting frames are designed to minimize the possibility of unintended vibration and misalignment.

The enabling simulation infrastructure of the 2PASD facility is the 2Simulate, an overall simulation framework to assist on the integration of models and simulation components [11]. It can modify and extent the predefined functionalities and reference model structures of the manufacturer. The software also operates in the AVES (Air VEHICLE Simulator). The control loading system is equipped with two pairs of active sidesticks manufactured by Wittenstein Aerospace & Simulation GmbH. The pedal modules are also installed as part of active flight controls [13].

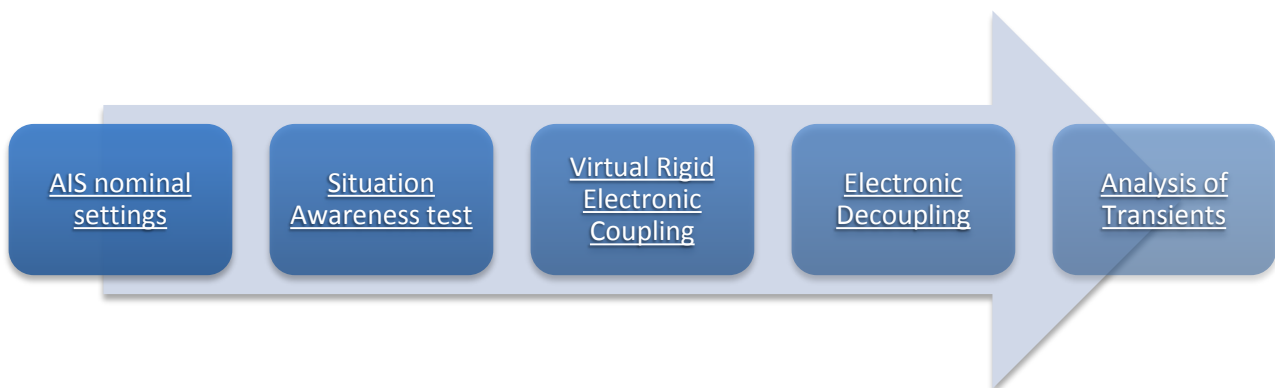


Fig. 2 – Methodology for evaluation of the AIS electronic coupling.



Fig. 3 - Dual Pilot Active Sidestick Demonstrator -2PASD

The generic sidestick grips were replaced by an inceptor equivalent to the one used on the EC-135 helicopter, including suitable plug-connection. As part of grip-interface, provision on the communication bus enables the operation of 14 digital inputs, making possible the functions of grip buttons, beep-trim and 4-axis switch.

Table 1 presents the FOV (Field of View) and the specifications of the system.

Table 1: 2PASD Visual System settings

	<b>2PASD</b>
Simulator Type	Ground-based ( <i>Rack type</i> )
FOV - Horizontal	±80°
FOV - Vertical	+20°; -30°
Image generation	5 monitors LED 55 inches
Native Resolution	1280 x 1024

In the 2PASD visual system, three graphic computers manage the computational power needed to generate the image outputs and a separate computer controls four touchscreen displays of 43 cm (17 inches). The software 2Indicate implements instrument panels or simulation control device on displays in both pilot stations.

### 3. EXPERIMENTAL SETUP

#### 3.1. System Design (EC-AIS)

Prior the development of the functions for the new pilot's inceptors system, an extensive study regarding posture, feel characteristics, and controllability was performed. The features developed in the Active Control System are summed up in the Fig. 4.

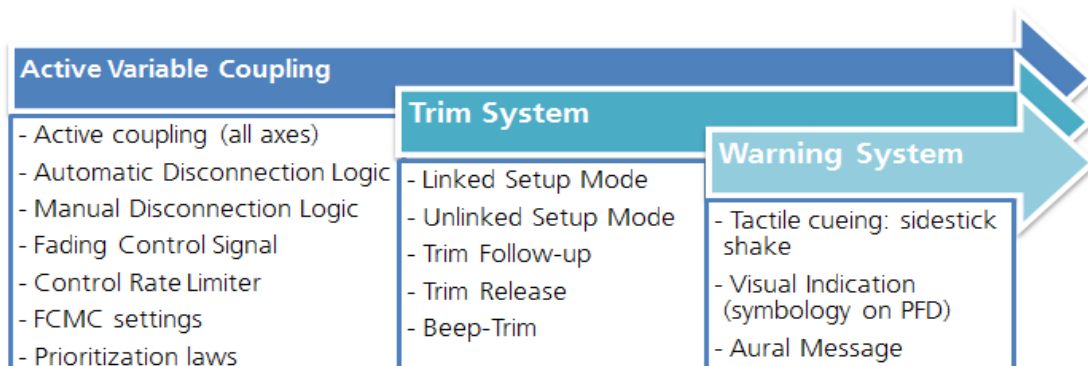


Fig. 4 – Features of the electronic coupling system.

The active sidesticks allows different possibilities of coupling and logics to prioritize one control station.

In the 'linked' mode, the forces applied to one sidestick are transmitted to the other, which is useful to emulate the mechanical linkage of coupled inceptors.

In the 'unlinked' mode, the algebraic summing of the sidesticks positions is averaged as output control signal. In case of simultaneous inputs of both pilots, the resulting signal is saturated when a value corresponding to the maximum deflection of one sidestick is reached. For example, if one stick is moved fully backwards and the other fully forwards, the resulting command is zero. Also, if both sidesticks are moved half way backwards, the resulting command is equivalent to a single sidestick moved fully backwards.

An automatic disconnection of the electronic coupling was implemented based on the pilot's activities on controls, particularly the force applied by each pilot on the same axis. If the limit of the force threshold is surpassed in one axis, it causes the disconnection of the electronic coupling in all axes. Another design consideration is the definition of which control station will fly the helicopter and which one will have the inputs signals canceled in the flight control system (one pilot priority).

Alternatively, a manual decoupling can be activated by the use of a priority pushbutton on the cyclic lever.

Any discontinuity in the flight control system without providing the proportionate awareness could trigger catastrophic effects. The dedicated warning system was developed to mitigate the risk of pilot's failure to recognize modifications on the coupling status. It is comprised of visual symbology on the PFD (Fig. 5); aural messages and tactile cueing (stick shaker).

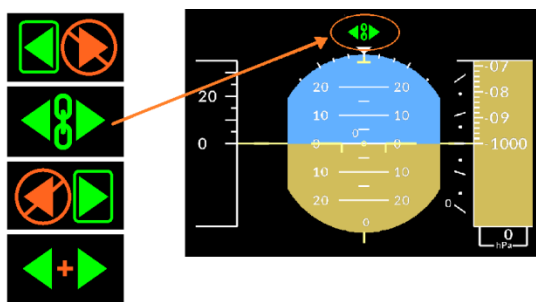


Fig. 5 – Coupling Visual Warning Symbology (left side) and position on PFD.

### 3.2. Evaluations

As experimental pilots (EP), five pilots assigned ratings for instructional tasks in the dual helicopter cabin. Their experience is shown in Table 2.

Table 2: Pilots Experience

Background	Experimental Pilots				
	A	B	C	D	E
Total Flight Hours	3500	2500	1800	6200	450
Helicopter Instructor	Yes	No	Yes	Yes	No
Test Pilot	Yes	Yes	Yes	Yes	No
Flight Experience (years)	20	24	17	39	09

For this work, flight instruction includes not only initial pilot training, but also work toward advanced certificates or ratings, transitions into unfamiliar aircraft, and recurrent instruction such as flight reviews [14]. The instructor pilot is defined as the person responsible to train the student pilot and teach the skills necessary for the student to operate safely and competently as a certificated pilot [15]. The EP flew as instructor pilots and were exposed to the same maneuvers and conditions (i.e. intensity and amplitude of student input errors).

The participation of the pilots in the tasks is described in the Table 3. Two of the pilots are not helicopter instructors (pilots B and E). This is considered acceptable for this study due to the experience of the pilots. Pilot B has extensive experience as a test pilot in helicopter industry, whereas Pilot E participated only in the Situation Awareness test. The student pilot in all tasks was Pilot C, except when he was the EP. In the latter case, Pilot E flew as the student pilot.

Table 3: Evaluations and Tasks Performed

Evaluation (Tasks)	Experimental Pilots				
	A	B	C	D	E
Situational Awareness Test (Reposition)	x		x	x	x
Questionnaire - Pilot Rating (Reposition; Collision Avoidance; and Hover)	x	x	x	x	
Analysis of Transients (Collision Avoidance)			x		

During the Situation Awareness test, EPs performed 5 trials in each coupling type (linked and unlinked mode), alternating after each trial. The initial mode was also changed for each pilot. The linked and unlinked modes remained constant during the same experimental trial (no disconnection). The objective measure of SA is achieved through the Situation Awareness Global Assessment Technique (SAGAT), as described by Endsley [16]. It employs periodic, randomly-timed freezes in a simulation scenario during which all of the operator's displays are temporarily blanked. Sixteen queries were determined based on the cognitive task analysis (Appendix B). The queries typically cover all three levels of SA (perception, comprehension and projection).

Concerning the second set of evaluations, a post-study questionnaire (Appendix C) is used to gather pilot ratings. The questionnaire is comprised of the first 9 out of the 11 requirements as indicated in the Table 4. The list of 11 of requirements is selected based on the Aerospace Recommended Practice (ARP) 5764 [17]. This is a SAE Aerospace document which describes the recommended key characteristics and design considerations for AIS. It should be noted that the items of the ARP 5764 are geared to FBW aircraft and lack suitability analysis for helicopter demands. Therefore, the evaluations intend to fill the gaps of the AIS design for helicopter application.

The quantitative analyses of the transients due to delinking (requirements 10 and 11 of the Table 5) were performed by one test pilot acting as instructor pilot. This set of tests focused on the change in helicopter state (attitude, attitude rate and angular acceleration) immediately after the disconnection. Seven levels of force threshold and four types of fading control signal were tested. The lateral axis was chosen because, among the axes controlled by sidesticks, it represents the worst-case condition in terms of dynamics and the rate response. After each test point, the assessing pilot awarded a rating for the resulting transient effects of the disconnection using the Transient Rating Scale (Appendix D).

Table 3 indicates the tasks performed for each evaluation. Full performance of the three tasks is contained in Appendix A (Flight Test Card). For completeness, the tasks are summarized below.

In the "Transverse Reposition" task, the instructor should limit the control or apply inputs to one axis when it is applicable due to the performance of the

pilot in command or due to safety (obstacle clearance).

The "Crane Collision Avoidance" task was evaluated in two speeds: 60 kt and 90 kt. As illustrated in the upper image of the Fig. 6, the student pilot flies in low level flight. He turns towards an area where a crane is placed and maintains bank angle of 30°. The instructor pilot should invert the bank angle to start a takeover maneuver, return to level flight as soon as possible and avoid the collision.

The third task is the "Hover over Helipad", as shown the lower image of Fig. 6. After an inappropriate input of the student pilot during the hover in-ground effect, the instructor should take control according to his judgment to avoid a collision or a loss of control condition.

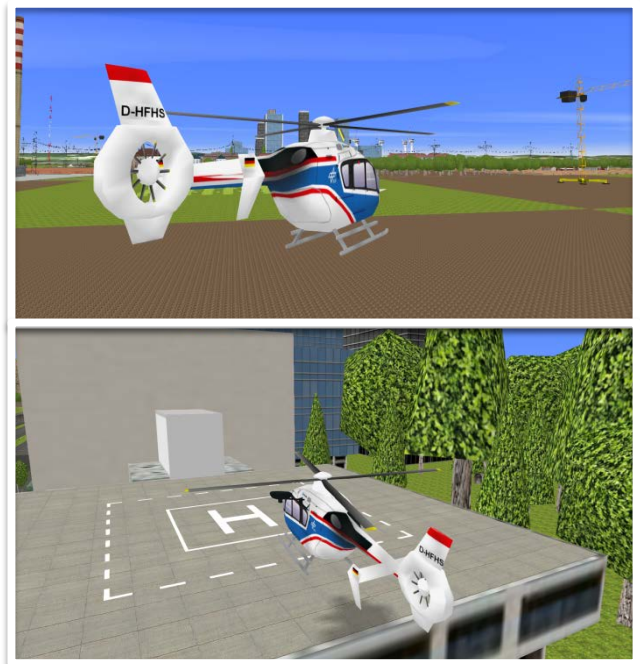


Fig. 6 – Crane Avoidance and HoverTask.

## 4. RESULTS AND DISCUSSION

### 4.1. AIS Nominal Settings

The nominal static FCMC for the cyclic sidestick is represented by the force deflection curves in the Fig. 7 and 8 for the Attitude Command response type. Simulator practices for the hover and slalom test [17] optimized the parameters. The cyclic sidesticks nominal settings are described in the Table 5. The feel characteristics on each inceptor-type after a decoupling remained the same in all experimental trials.

Table 4: List of Requirements and Evaluations

Evaluation	Task (Test Point) <sup>1</sup>	Criteria	Topic	RQMT #	Requirement Description	ARP5764 #
Situation Awareness test	Transverse reposition (TP1)	SAGAT survey <sup>2</sup>	Situation Awareness	-	Comparative analysis of coupled and uncoupled inceptors by Situation Awareness Global Assessment Technique	-
Virtual Rigid Electronic Coupling	Transverse reposition (TP2)	Questionnaire <sup>3</sup> (ARP 5764)	System Performance: Operational Modes	1	Active Mode: 'Linked' operation in dual seat cockpit	3.2.1.1
			System Performance: Dynamic Performance	2	Cross-Axis Coupling: Cross coupling effects minimized	3.2.2.12
				3	Cross Cockpit Coupling: Mechanical linkage is simulated and intervention allowed	3.2.2.13
			System Design: Dual Seat Considerations	4	Linked Inceptors to ensure that pilot and copilot inputs are coordinated/consistent	3.3.1.6/ 3.3.3.6 a)
Electronic Decoupling	Crane Collision Avoidance (TP3) and Hover over Helipad (TP4)	Questionnaire <sup>3</sup> (ARP 5764)	System Design: Dual Seat Considerations	5	Disengage threshold disconnects inceptors in case of 'Force fight' between pilots	3.3.1.6/ 3.3.3.6 b)
			System Design: Typical Operating Characteristics	6	Capability to overpower/override controls during active mode operation via pushbutton (disengage switch)	3.3.1.5.3/ 3.3.3.5.3
			System Design: Dual Seat Considerations	7	Post-Decoupling logic: averaged inceptor position or one station priority	3.3.1.6/ 3.3.3.6 d)
Analysis of Transients	Crane Collision Avoidance (TP3) and Hover over Helipad (TP4)	Questionnaire <sup>3</sup> (ARP 5764)	System Design – Dual Seat Considerations: Transients Associated with Linked Inceptor	8	Linking results in minimum transients in position	3.3.1.6.1/ 3.3.3.6.1 a)
				9	Linking operation in case of mismatched sidesticks	3.3.1.6.1/ 3.3.3.6.1 b)
		Quantitative Analysis		10	Gradual delinking without sudden transients	3.3.1.6/ 3.3.3.6 c)
				11	Fading time to delinking	3.3.1.6.1/ 3.3.3.6.1 c)

1- Appendix A – Flight Test Card; 2 - Appendix B – SAGAT Survey; 3 - Appendix C - Questionnaire.

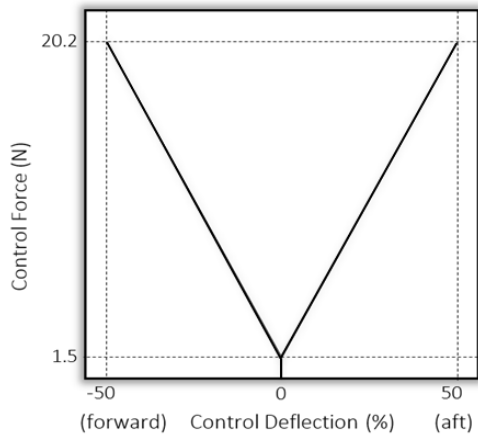


Fig. 7 – Static force-deflection characteristics (pitch)

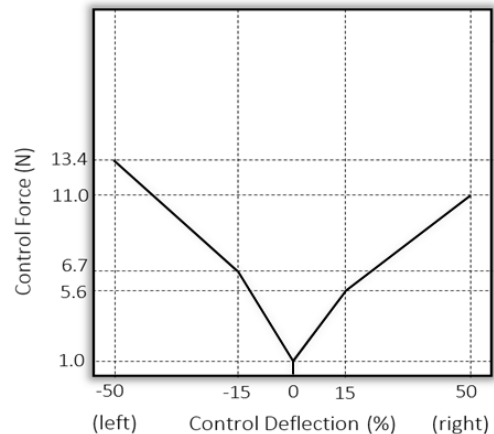


Fig. 8 – Static force-deflection characteristics (roll).

Table 5: AIS Nominal Settings for Pitch and Roll axes

Parameter	Value
Control Travel	$\pm 49.98$ mm; or $\pm 17^\circ$
Grip reference point	165.5 mm
Frequency	4.0 Hz
Damping Ratio	1.2 (-)
Breakout Force	1.5 N (Pitch); 1.0 N (Roll)

#### 4.2. Situational Awareness Test

The 16 SAGAT queries (see Appendix B) were randomly selected. Each pilot answered a total of 23 questions for each active inceptor design, linked and unlinked. Fig. 9 shows the percentages of correctness to the SA questions.

McNemar exact test determines whether there is a significant SA difference between the pilots flying with linked inceptors versus unlinked inceptors.

The p-values are generated by testing whether the proportion of discordant pairs (different outcome on each design) is greater than 0.5. If the proportion of discordant pairs is different from 0.5 (higher or lower), then there is evidence of a difference between designs. Table 6 sums up the paired nominal data. The null hypothesis was rejected ( $p < 0.01$ , significance level 0.05), since the awareness for the linked and unlinked inceptors is not equally likely.

The statistical test indicates a 99.75% chance that the SA is different, and 99.9% chance the linked inceptors provide a higher SA. The difference

between proportions is 16% and the 95% confidence interval around the difference is  $\pm 10\%$ .

The questions 1, 7 and 13 (Appendix B) addressed the inputs applied by the student pilot at the moment of the freezing. For each type of coupling (linked and unlinked), a total 15 answers for these questions was extracted to new statistical analyzes. Without the force feedback of the linked design, pilots using the uncoupled inceptors should answer based on visual cueing, like helicopter attitude changes and panel information (PFD).

The percentages of correctness and pairwise data of the SA questions addressing inputs of the other pilot are showed in Fig. 10 and Table 7.

Again, the null hypothesis was rejected ( $p < 0.01$ , significance level 0.05). There is a 99.6% chance the awareness of the other pilot inputs is different between the types of coupling; and 99.8% chance the linked inceptors lead to higher SA of the student actions on controls. The 95% confidence interval around the difference between designs is 74% to 21% (difference of 53%).

Pilots suggested that the uncoupled inceptors led to a significant increase of workload to correct inputs of the student in comparison to the linked controls. All the experimental pilots strongly agreed that the linked sidesticks are better to monitor the performance of pilot flying and raised the perception of an inappropriate control input of the other pilot. One test pilot mentioned that, as an instructor, "it is almost impossible to monitor control input without coupled controls". Another consideration was that uncoupled controls are "more mentally demanding" for the instructor.

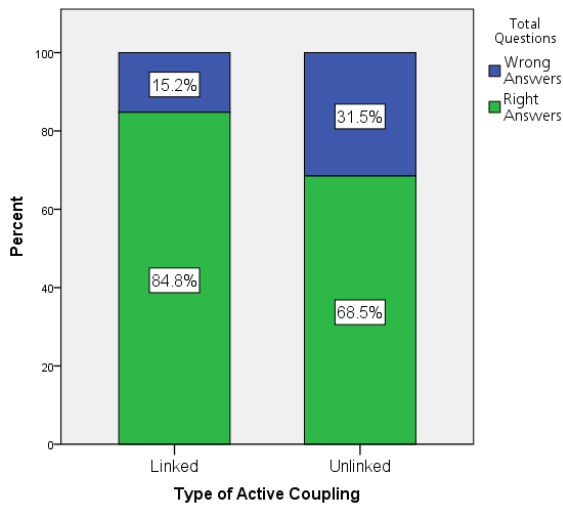


Fig. 9 – Total Answers to SA survey.

Table 6: Cross-tabulation of Total Questions

		Unlinked Inceptors		Total
		Wrong Answers	Right Answers	
Linked Inceptors	Wrong Answers	9	5	14
	Right Answers	20	58	78
Total		29	63	92

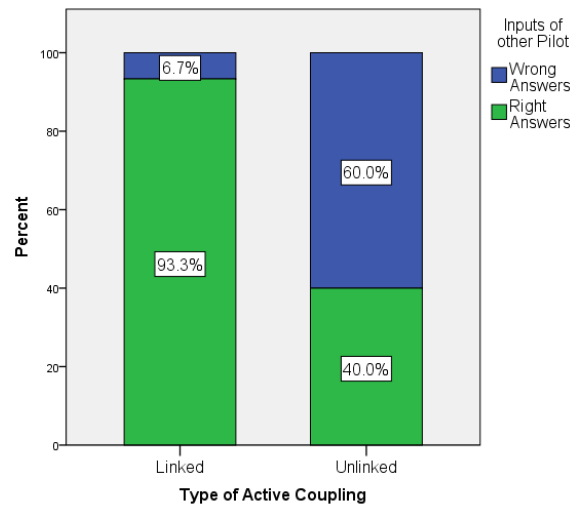


Fig. 10 – Answers addressing Inputs of other Pilot.

Table 7: Cross-tabulation of Input Questions

		Unlinked Inceptors		Total
		Wrong Answers	Right Answers	
Linked Inceptors	Wrong Answers	1	0	1
	Right Answers	8	6	14
Total		9	6	15

### 4.3. Pilot Ratings for Questionnaire

Pilots rated the requirements (RQMT) 1 to 9 listed in Table 5 through the post-study questionnaire (Appendix C). The EPs specified their level of agreement or disagreement on a 7-points Likert scale to each RQMT, as shown in Fig. 11. In this bipolar symmetric scaling method, the maximum value relates to the maximum agreement to the sentence, and vice-versa. The middle value indicates neutral opinion.

The mean of pilot ratings obtained are shown in Fig. 12. The first four RQMT focused on the Virtual Rigid Electronic Coupling analysis. The follow-through technique (resting hands on controls) to monitor sidestick inputs of the other pilot was extensively employed and was useful to evaluate the linked operation.

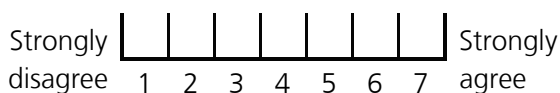


Fig. 11 – 7 Points Likert-Type Rating Scale.

Pilots considered the system capable to emulate the mechanical linkage between control stations. To reproduce such case, the force fight threshold was set to 220 N, a greater value than usual forces in helicopter inceptors.

Full interventions by instructor pilots were effectively accomplished and the performance of the electronic coupling for takeover control was alike the true mechanical one.

For RQMT 2, the cross coupling effects of the linked mode in the helicopter response was considered difficult to assess, because the helicopter model caused minor side effects in attitude response. However, pilots reported that no objectionable deflections were identified in cross-axis inputs.

Regarding the automatic disconnection, pilots tested the force threshold range from 5N to 40N as the automatic disconnection during takeover maneuvers. A low force level generally leads to small transients in attitude. Surprisingly, very low thresholds (5 to 15 N) were rejected by the pilots, since it generates unintentional decoupling and confusion about the disconnection occurrence.

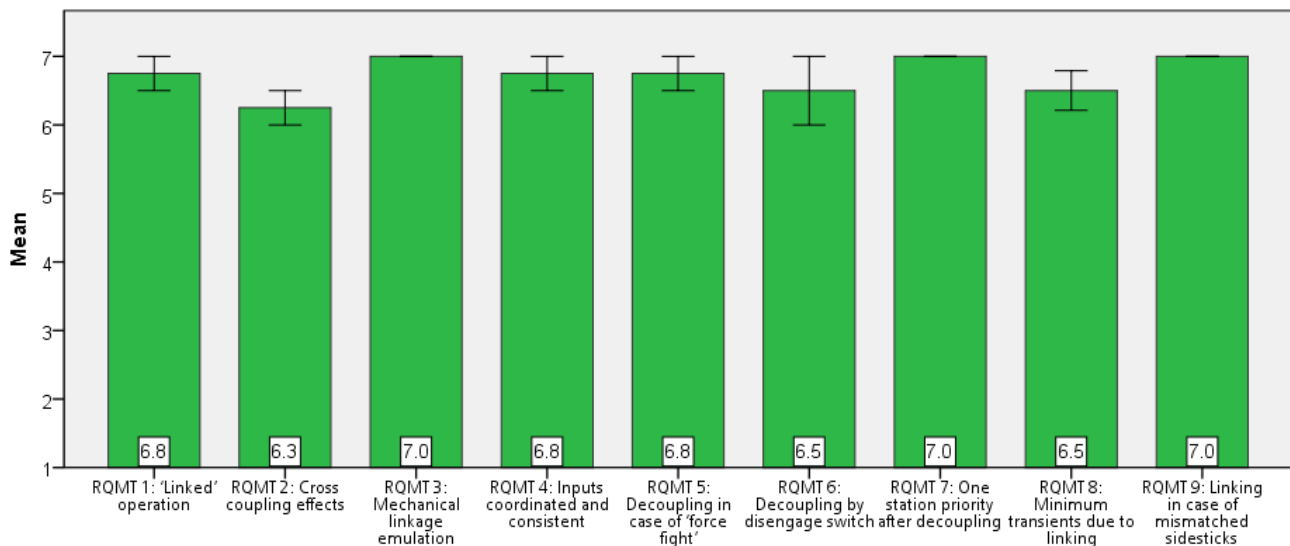


Fig. 12 – Pilot Ratings for Requirements 1 to 9 (Error Bars:  $\pm 1$  Standard Error).

From 20 N on, only deliberate disconnections took place. Objectionable transients were identified in force threshold of 30 N and higher, but the range of 20 to 25 N was classified as “transients expected due to the dynamics of the takeover maneuver”. The largest rating deviation is related to disconnections by pushbutton. Pilots reported no major consequences or system failures. However, they indicated that “it is not the most intuitive reaction to a collision risk in dynamic maneuvers”.

The preferred post-decoupling logic, between the averaged inceptor positions and the prioritization of one control station (pilot or copilot), was the latter. In the averaged positions logic, pilots frequently were unable to avoid LOC or collision to obstacles.

For the linking analysis, the transition from the uncoupled to coupled status is made by pushbutton on the cyclic control. Test pilots reported no perceptible influence of the mismatched sidestick positions to the controllability while linking sidesticks. However, the system indicated a limitation in the use of trim system, due to the influence of the inoperative sidestick for the uncoupled condition. Later on, the system was optimized according to the pilot comments.

#### 4.4. Analysis of Transients

An in-depth quantitative analysis of the decoupling effects was conducted. The Transient Rating Scale used was developed by Hindson et al. [19] in support of the development of an experimental fly-by-wire helicopter, and modified by Weakley et al. [20].

It is a decision tree based scheme with two columns corresponding to transient response and recovery from a sudden degradation. Each column can be rated from A to H. The results in this paper concentrated on the transient response only. There are two leading questions, concerning the impossibility to perform the task and if the safety was compromised. The answers ‘no’ for these questions lead to the tolerable category (i.e., ratings from A to E).

The task of “Crane Collision Avoidance” is a time critical condition. The instructor pilot should takeover control from the student and no time for verbal interaction is available. Seven levels of force threshold (FT) and four types of fading control signal were tested. Two main criteria are applied:

- Uniform and predictable change in the helicopter states (subjective criterion); and
- Minimum control excursions and helicopter attitude transitions (quantitative analysis).

Regarding the force threshold variation, more than 80 test points were rated by one test pilot. Confidence in the rating assignment is considered adequate through the variation showed in Fig. 13. The roll rate ( $p$ ) and bank angle ( $\phi$ ) increase in nearly linear fashion. Ratings awarded using the Transient Rating Scale are denoted by colors. As shown, the pilot rating progressively degrades with distance from the origin, which reflects an intuitively appropriate effect. Moreover, mean averages ( $p$  and  $\phi$ ) are statistically different from each other, if classified by the pilot rating.

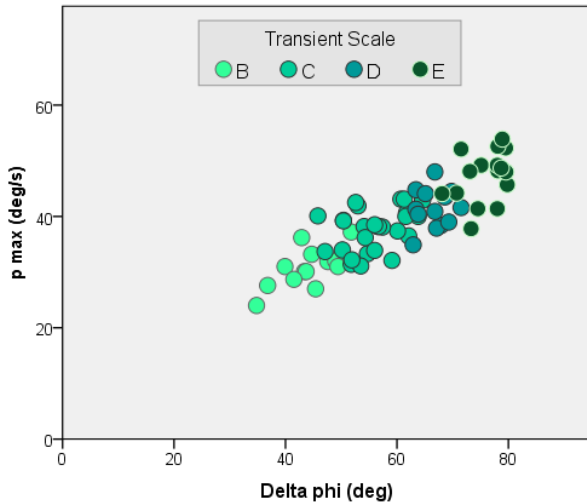


Fig. 13 – Transient Rating in Takeover Task. Roll Rate over Bank Angle after Decoupling.

Analysis of Variance (ANOVA) reveals that not all the means compared in the test are equal ( $p < 0.01$ ). Subsequently, a post hoc test calculates multiple t-tests. Fisher's least significant difference (LSD) indicates significant difference to all pairs of means ( $p < 0.01$ ), either for  $p$  or change in  $\phi$ .

In Fig. 14, the time to disconnect is the time between the initial instructor input to override controls and the moment the inceptors automatically decouple. It is worth mentioning that previous research has identified the usual reaction time to a linked control as 2 seconds [21]. Thus, the opposing force of the student pilot is a feasible action within the seven thresholds tested.

According to the ratings assigned by the pilot, the lower force threshold is associated to fast disconnections and small changes in attitude and control deflections. Higher threshold brings longer 'force fight' on controls.

The disconnection without sudden transients is achieved in the interval of FT 5 to 20N, because no objectionable excursions in controls and helicopters state were commonly verified. Above 25N, the control disconnection impacts the controllability, and overshoots are usual. Above 40N, all controls must be adjusted to compensate the decoupling, and operational flight envelope can limit the actions. Thresholds higher than 48N were not rated, because it led mostly to the intolerable region of the scale (F to H).

Regarding the fading control signal variation, the FT was kept as 20N for all four options tested in more than 80 test points. The fading function reduces the control input gain after the decoupling.

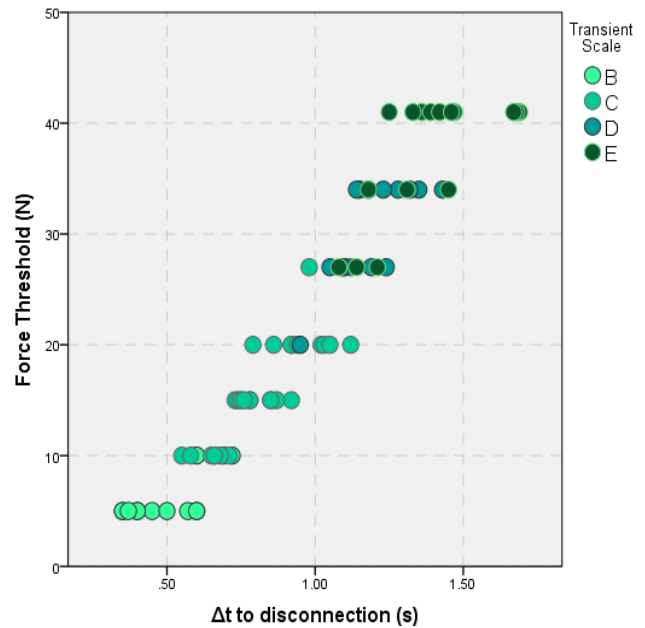


Fig. 14 – Transient Rating in Takeover Task, Time to Decouple Inceptor over Force Threshold.

The fading is defined as the time in seconds to regain full control power (instructor). In the 'fading control signal 2', for example, an inceptor input of 10% is decreased to 5% right after the decoupling. If the inceptor is maintained in that position, the signal sent to the flight control computer (FCC) increases gradually to 10% in 2 seconds. Hence, the consequences of the likely overshoot in the control deflection after the decoupling can be attenuated.

Fig. 15 illustrates the four fading control signals tested (fading 0, 1, 2 and 3). Even delaying in 1 sec the full control power, 'Fading Signal 1' allowed the instructor pilot to deflect the inceptors laterally in a smooth and continuous fashion. As consequence, the bank angles on average are lower than the 'Fading Signal 0' to perform the takeover maneuver.

In 'Fading Signal 0', the disconnection is virtually immediate, and precipitates a stepwise control signal in the FCC due to the control position split after disconnection. In this case, transition triggers a sudden roll rate and does not represent the uniform and predictable helicopter response generally required by pilots. Fading Signal 2 and 3 were considered too slow by pilot. The EP reacted increasing the inceptor deflection to compensate the lack of control power. Without the expected answer to the input, the pilot excessively deflects the inceptor.

Fig. 16 shows the comparison of the fading control signals to other parameters. Besides the lower mean roll rate and angular velocity, Fading Signal 1 resulted in less control deflection and bank angle to perform the same task. Although it is not the fastest option to bring the helicopter to level flight, Fading Signal 1 was the fastest alternative to complete the maneuver, which included the takeover control and the collision avoidance.

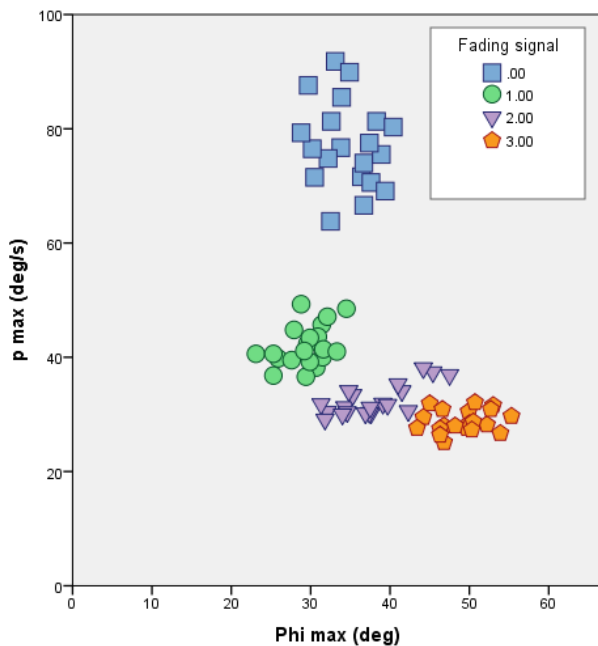


Fig. 15 – Fading Control Signal in Takeover Task, Roll Rate over Bank Angle.

This outcome exposes the capacity of the pilot to compensate delays of 1 second in control power without impacting significantly the controllability. It is meaningful because future functions that require a fading control signal to mitigate failure transients can apply such interval.

In all cases, the prevailing transients in control position due to the decoupling are not prevented, but the functions ameliorate the effect on the attitude response and improve the takeover maneuvers performed by instructor pilots.

## 5. CONCLUSIONS

The work presents an innovative methodology to evaluate the electronic coupling of active inceptors for dual pilot helicopters. The following are the outcomes of the study:

1. In the Situation Awareness tests, a statistically significant difference was verified for linked inceptors in comparison to unlinked ones. There is 99.9% chance that the linked inceptors provide higher overall SA. Test pilots indicate that linked inceptors are better to monitor the performance of pilot flying, raising the perception of an inappropriate control input of the other pilot and decreasing workload to correct inputs of the student.
2. For the analysis of the electronic connection to emulate of mechanical linkage between control stations, full interventions by instructor pilots were effectively accomplished and the performance of the electronic coupling for takeover control was alike the true mechanical one.
3. During active mode operation, the system provided capability for pilot overpower/override, via pushbutton and via force threshold. In the optimum setting, the instructor could intervene without significant over-control when taking over.
4. The logic to average the inceptor position after a disconnection as the FCC input was rejected by pilots, and the prioritization of one control station (pilot or copilot) is pointed as the recommended logic to helicopter flights near obstacles.
5. The analysis of transients in automatic disconnections due to force thresholds indicates that no objectionable excursions in controls and helicopters state were commonly verified in the interval of force threshold 5 to 20N.
6. A fading function that gradually transitions the control power from the control coupled state (linked mode) to the one pilot flying condition (unlinked) was implemented. Fading control signal of one second shows beneficial effect to the takeover maneuvers that require high agility. In contrast to the configuration without this function, 1-sec fading reduced roll rate and angular velocity, and still demanded less control deflection and bank angle to perform the same task.

## 6. FUTURE WORK

Introduction of discontinuities in flight control chain is a major challenge in most of helicopter scenarios. Future evaluations shall continue to investigate the interference in controllability without excessively limit the actions of pilots.

The fading functions, albeit the promising results, only focus on attitude response alleviation. Therefore, the introduction of active functions to modify the gradient of the force deflection curves shall still be assessed.

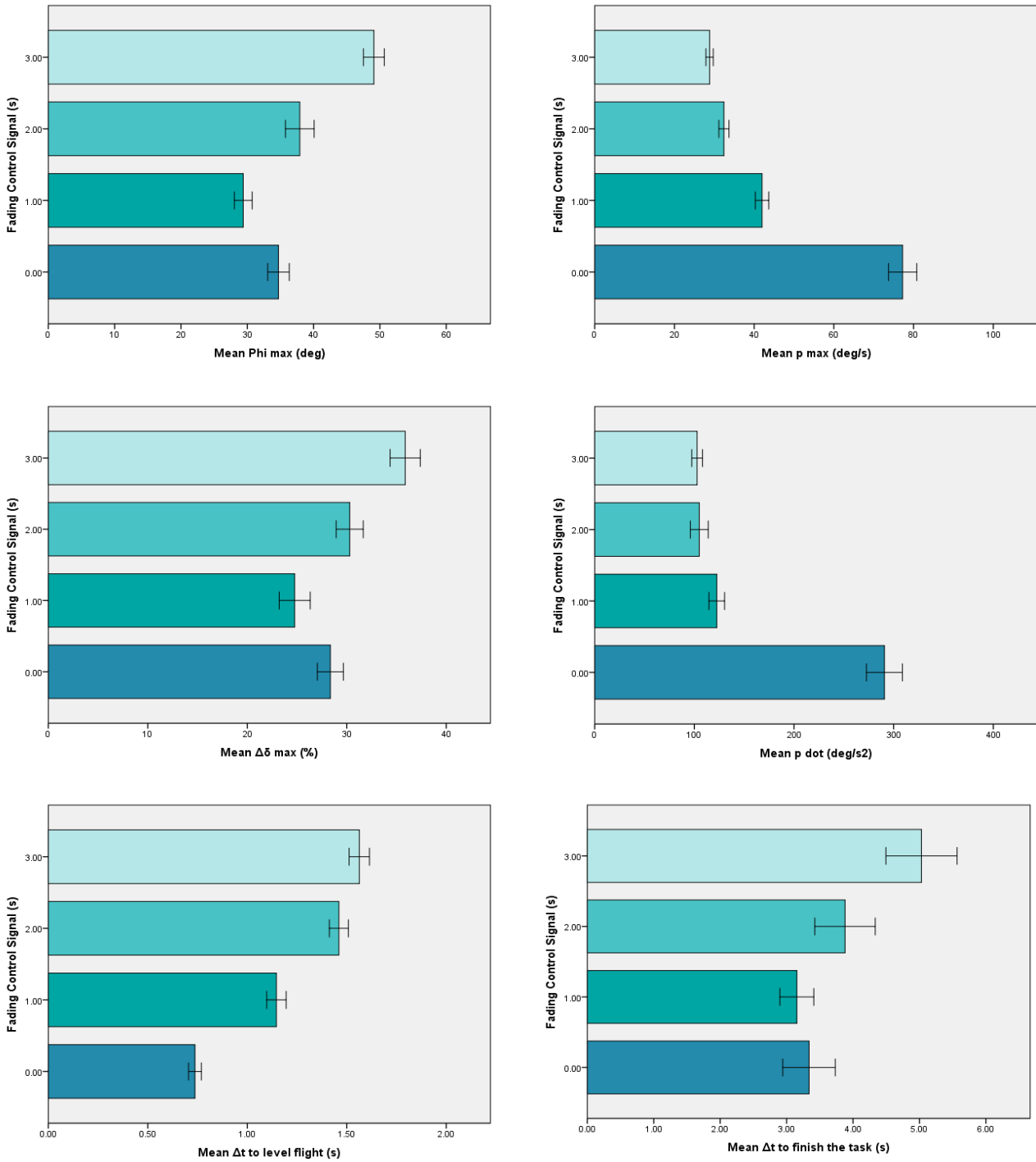




Fig. 16 – Fading Control Signal for takeover maneuver in the Crane Collision Avoidance task  
(Error Bars: 95% of Confidence Interval)

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## APPENDIX A - Flight Test Card

				<h1 style="margin: 0;">Flight Test Card</h1> <p style="margin: 0;">Page 15 / 20</p>		
Date TBD	n <sup>th</sup> Run	Status Simulator Flight 2PASD	A/C EC135 FHS	S/N	Call Sign D-HSIM	Crew SP/EP TDB

### Test Technique - Transverse Reposition

**a. Objectives.**

- Check usefulness of the follow through technique to monitor sidestick inputs of the other pilot.
- Check situation awareness for comparison of flight control cross-cockpit couplings.
- Check ability to recognize the flight control cross-cockpit coupling status through tactile warnings.
- Check for objectionable transients in take over control maneuvers (without disconnection).
- Check the force threshold suitability.

**b. Description of maneuver (Test Points 1 and 2).**

The safety pilot flies as the student pilot, and the experimental pilot act as the instructor. Starting from a stabilized hover with the longitudinal axis of the rotorcraft oriented approximately 45 degrees to the reference grass marked on the ground; initiate the maneuver at a ground speed of between 10 and 20 knots, at an altitude between 40 and 60 ft. The instructor helps limiting the control or applying inputs to one axis when it is applicable due to the performance of the pilot in command or due to safety (obstacle clearance). The interactions can be partial intervention (helping in one axis) or full intervention (taking over controls). Repeat the maneuver in the opposite direction. Afterwards, the roles are inverted: EP flies, and SP interferes on controls. The experimental pilot (PF) communicates when he feels that the pilot monitoring applies inputs on controls or when the controls are disconnected.

**c. Description of test path.**

The test path shall consist on the reference grass line indicating the desired track. Any feature of the scenario can be considered as an obstacle (building, trees, traffic lights, etc). The final point of the maneuver is the X point before the power line.

### Test Technique - Crane Avoidance

**Objectives.**

- Check for objectionable transients in take over control maneuvers (with disconnection).
- Check capability for pilot overpower/override during active mode operation.
- Check the FCS post-delinking law: averaged stick positions or one cockpit priority.
- Check the fading time constant to the linking or delinking of the inceptors.

**b. Description of maneuver (Test Points 3).**

The safety pilot flies as the student pilot, and the experimental pilot act as the instructor. At two speed conditions (60 and 90 kt), the student pilot initially flies the helicopter in straight forward low level flight. He starts a turn towards an area where a crane is placed. This obstacle is at 210 m away from the point of the initial lateral input. At a distance of 150 m, the bank angle of the helicopter is 30° (± 2°) and the instructor pilot should invert the bank angle to start a takeover maneuver. Right after, the pilot should return to level flight as soon as possible. The difference of distance between the initial input and the instructor pilot counteraction corresponds to the instructor reaction time. Repeat to perform either with manual or automatic disconnection.

**c. Description of test path.**

The test path and the point to start the takeover maneuver are indicated on the ground. The minimum allowed distance of the helicopter to the crane is 30 m.

### Test Technique - Hover Takeover Control

**Objectives.**

- Check for objectionable transients in take over control maneuvers (with disconnection).
- Check capability for pilot overpower/override during active mode operation.
- Check the FCS post-delinking law: averaged stick positions or one cockpit priority.
- Check the fading time constant to the linking or delinking of the inceptors.

**b. Description of maneuver (Test Points 4).**

The safety pilot flies as the student pilot, and the experimental pilot act as the instructor. The task consists in hover IGE over a helipad. No specific point or moment to takeover is indicated. Thus, the instructor should take control according to his judgment to avoid a collision or a loss of control condition. Perform takeover maneuvers at any time to avoid collision to the helipad or obstacles around it.

**c. Description of test path.**

The helicopter should stay within the limits of the helipad in controlled conditions.

#### For all Tasks

**Performance standards.** Accomplish the task, and interact on flight controls when applicable. The aircraft shall stay within the conditions defined in the test point.

#### Test Program

Purposes	Coupled Sidesticks assessment
Configuration	Cyclic and collective Sidesticks; conventional pedals; dual pilot cockpit
CLS Manufacturer	Wittenstein
Subject Groundwork	Questionnaire: Notes, Background and Expectation section

TP	1	TRANSVERSE REPOSITION: FOLLOW THROUGH TECHNIQUE			
Technique	As described on "Test Technique"	Limits	FLI 78%		
Procedure	a) Perform the task as the instructor pilot (PM). b) In order to monitor the other pilot inputs, apply the "follow through technique". c) Interact on the controls as applicable, either by partial intervention (helping in one axis) or by full intervention (taking over controls). d) When the scene is frozen, answer the SAGAT questionnaire. e) Repeat for the uncoupled controls condition. f) Repeat once the task as the Pilot Flying (PF). g) When the trials are finished, answer to the interview.	Condition	Speed	15 KIAS	
			Heading	230°/050°	
			Height	50 ft	
			CLS	TBD	
		Tolerance	Speed	± 5 KIAS	
			Heading	± 10°	
			Height	± 10 ft	
			Distance to obstacle	± 10 ft	
Notes	SAGAT queries, answer to questionnaire (section 4), pilot's observations.				

TP	<b>2</b>	<b>TRANSVERSE REPOSITION: LINKING PERFORMANCE AND AIS WARNING</b>		
Technique	As described on "Test Technique"		Limits	FLI 78%
Procedure	<ul style="list-style-type: none"> <li>a) For each of the eight levels of force threshold, the student pilot drifts or applies wrong inputs.</li> <li>b) The experimental pilot, acting as the instructor, intervenes through limiting the controls if tolerances are exceeded or due to safety (i.e. obstacle collision, over torque).</li> <li>c) EP performs full intervention (take over controls) only if it is judged necessary (last case).</li> <li>d) At the end or in the case of collision, the EP indicates: number of lights and the last one.</li> <li>e) EP indicates the case of inadvertent unlinking.</li> <li>f) Repeat for tactile warning.</li> <li>g) At the end of the session, perform a traffic pattern to analyze the linking operation. At any moment, uncouple and couple the controls again by pressing the pushbutton.</li> </ul>	Condition	Speed 20 KIAS Heading 230°/050° Height 40 ft CLS Coupled	
		Tolerance	Speed ± 5 KIAS Heading ± 10° Height ± 10 ft Long. ± 10 ft Error	
Notes	Answer to questionnaire (section 5), answer to the interview (section 7), and force threshold (FT) suitability.			

TP	<b>3</b>	<b>EVASIVE MANEUVER: CRANE COLLISION AVOIDANCE</b>		
Technique	As described on "Test Technique"		Limits	FLI 78%
Procedure	<ul style="list-style-type: none"> <li>a) Perform the task as the instructor pilot (PM).</li> <li>b) After the takeover control maneuver, bring back <math>\phi</math> to 0° asap.</li> <li>c) Variables: fading control signal, disconnection means, and FCS post-delinking law.</li> <li>d) When trial is finished, answer the survey.</li> </ul>	Initial Condition	Speed 60 or 90 KIAS Heading 045° Height 80 ft CLS Coupled	
		Tolerance	Speed ± 5 KIAS Heading ± 10° Height ± 20 ft	
Notes	Failure Evaluation Scale, answer to questionnaire, fading control signal suitability, FT suitability.			

TP	<b>4</b>	<b>HOVER TAKEOVER CONTROL</b>		
Technique	As described on "Test Technique"		Limits	FLI 78%
Procedure	<ul style="list-style-type: none"> <li>a) Perform the task as the instructor pilot (PM).</li> <li>b) After the takeover control maneuver, bring back <math>\phi</math> to 0° asap.</li> <li>c) Variables: fading control signal, disconnection means, and FCS post-delinking law.</li> <li>d) When trial is finished, answer the survey.</li> </ul>	Initial Condition	Heading 270° Height 80 ft CLS Coupled	
		Tolerance	Heading ± 10° Height ± 15 ft	
Notes	Failure Evaluation Scale, answer to questionnaire, fading control signal suitability, FT suitability.			

## APPENDIX B - SAGAT Survey

Table 8 - Goal-directed task analysis.

Task	Goals	Sub goals	Decisions	Level 1 SA	Level 2 SA	Level 3 SA
				Perception	Comprehension	Projection
Flight instruction	Student pilot learning	Monitor performance	Suggest adjustments	Input: Axis Direction	Input: Axis Intensity	Future ctrl correction
	Safety: Avoid Accident	Clearance to obstacles	Control intervention	Nearest obstacle	Ctrl Strategy Vs. Obstacle	Most Unsafe obstacle
Task Performance	Speed maintenance	Speed tolerance	Correct inputs accordingly or suggest adjustments	Speed condition	Task: Speed tolerance	Next Speed Variation
	Heading maintenance	Heading tolerance		Heading condition	Task: HDG tolerance	Next HDG Variation
	Height maintenance	Height tolerance		Height condition	Task: Height tolerance	Next Height Variation
Secondary Task	Identify Lights on	Visualize	Memorize	Last light on	Task: number of lights on	-

Based on the goal-directed task analysis, the topics of the SAGAT queries are listed below (answer options).

1. Axis/direction of the student pilot input in the last 3 sec. (Left/Right/Forward/Backward)
2. The helicopter current position. (Location on the map)
3. The speed of the helicopter. (0 to 30, in blocks of 5 kt)
4. The heading of the helicopter. (Target  $\pm 20^\circ$ , in blocks of  $10^\circ$ )
5. The height of the helicopter. (30 to 70, in blocks of 10 ft)
6. The last light that turned on. (Cross the right light among the options)
  
7. Variation of pilot input intensity in the last 3 sec (No variation, Apparent variation)
8. Nearest obstacle in the last 3 sec (Location on the map).
9. Number of times that the helicopter has flown out of the speed tolerance. (0 to 5)
10. Number of times that the helicopter has flown out of the heading tolerance. (0 to 5)
11. Number of times that the helicopter has flown out of the height tolerance. (0 to 5)
12. Total number of lights on. (0 to 10)
  
13. Recommended control input to stay within the task parameters (Pitch forward/ Pitch backward/ Roll Leftward/ Roll Rightward)
14. Expected variation in speed in the next 5 sec. (Slower, No variation, Faster speed)
15. Expected variation in height in the next 5 sec. (Decrease, No variation, Increase Height)
16. Future position of the helicopter. (Location on the map).

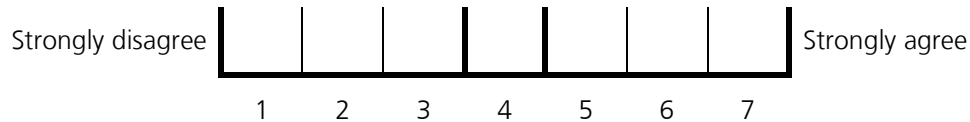
## APPENDIX C - Questionnaire

### 1. Briefing Notes

Information about the aim of the study, anonymity and voluntary issues (omitted). The questionnaire is based on the ARP 5764 [14].

### 2. Rating Scale

The participant shall indicate one cross in one space of the 7-points Likert scale to each sentence, as indicated below. The intermediate spaces between neutral (4) and the minimum/maximum values shall be used to indicate the degree of agreement or disagreement to the sentence.



### 3. Virtual Rigid Electronic Coupling (TP1)

- 3.1 The active coupling (EC-AIS) enable the 'linked' operation in the dual seat cockpit for helicopter flight.
- 3.2 The influence of the active flight controls (EC-AIS) to cross-axis coupling effects (one axis affecting a secondary/uncommanded axis) in minimum.
- 3.3 The EC-AIS fully provide the ability to intervene the other pilot's inputs up to a force level that simulates the mechanical linkage (i.e. instruction intervention).
- 3.4 In the 'linked' mode, the pilot and copilot inputs coordinated and consistent.

### 4. Electronic Decoupling (TP2)

- 4.1. The active coupling (EC-AIS) fully allow the disengagement of the flight controls in the case of 'force fight' if a certain level of opposing force is applied.
- 4.2. The system is fully capable to overpower/override control by the disengage switch on cyclic lever.
- 4.3. After a delinking event, the FCS (Flight Control System) should be programmed to follow one primary control station instead of use the averaged stick positions.

### 5. Analysis of Transients (TP3/TP4)

- 5.1. During the linking operation (uncouple to couple status), the transients in the position of the EC-AIS inceptors are minimum (slight influence on controllability).
- 5.2. In the case of cyclic sticks in different positions before the linking operation (uncouple to couple status), there is no consequence to the flight and to the cyclic linking operation.

## APPENDIX D - Transient Rating Scale

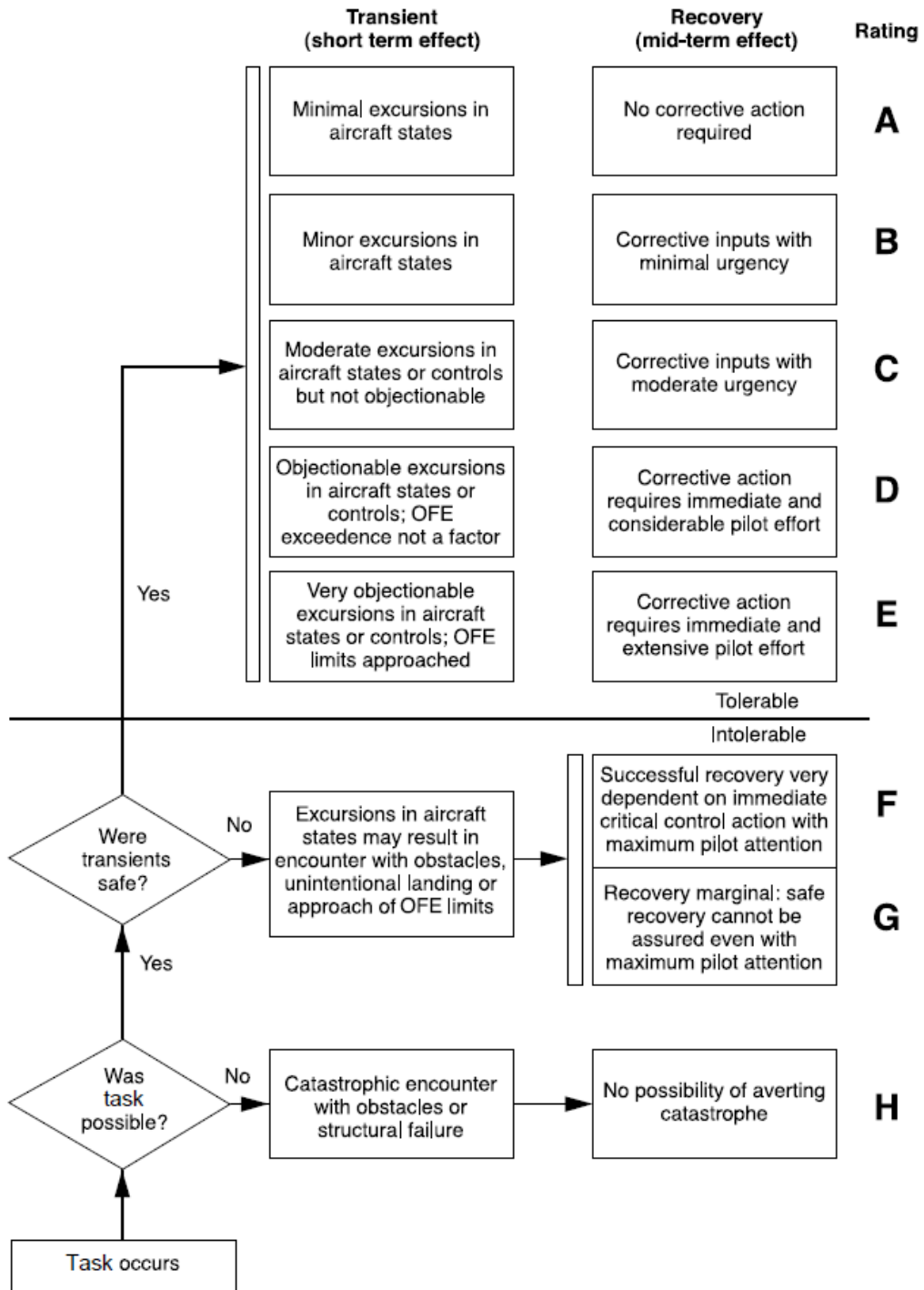


Fig. 17 - Transient and Recovery Rating Scale [20].