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A HUMAN-MACHINE INTERFACE ANALYSIS FOR TELEOPERATION OF UAV OVERTIME DELAY

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Abstract

The problem addressed in this research is the control of a remotely piloted aircraft using a satellite communication link with communication delay. To investigate the problem, it was necessary to build and investigate a test platform where the pilot could land an aircraft outside the standard operating area. The mission mandatorily depends on communication via satellite. The dynamic model of the aircraft used for the experiment was developed in the Matlab/Simulink software, with all inertial and aerodynamic modeling arrangements. The graphical interface for displaying the scenery, 3D model of the aircraft, and items used during the experiment are generated in the FlightGear software. The Unity software is used to develop a secondary interface that receives data from Matlab/Simulink. All tests studied were monitored through performance measurements, concerning deviations from the expected trajectory, using physiological sensors. The experimental data are processed to evaluate the influence of the predictive interface during flights performed with delay in the visualization.

Keywords: HMI, UAV, Prediction interface, Mental Workload, Physiological sensors

1. Introduction

As in other areas, aviation is moving towards the use of unmanned systems. These can operate in missions that demand long periods, in remote and hostile areas, without the need to embark on heavy and expensive life support systems, offering greater capacity payload per flight [1]. The Unmanned Aerial Vehicles (UAV) and Unmanned Aerial Systems (UAS) classifications refer to fully autonomous machines, but these vehicles depend on pilots, sensor operators, and maintainers. As a possible effect of these terms, there was a great focus on aircraft technology to the detriment of the human components of the system, being as serious as focusing on an airplane but excluding the cockpit [2]. A UAS is composed of a UAV, a Ground Control Station (GCS), and communication systems. The communication can be ground antennas, allowing the control of the UAV by Line-of-Sight (LOS), or satellite antennas, allowing in addition to the control of Beyond Line-of-Sight (BLOS). Other complementary elements for the operation determines the term “system”. The physical separation between the pilot and the aircraft, the control through radiofrequency signals, and a remote control interface are some of the particularities that introduce unusual human factors concerning conventional aviation [3].

Accidents and incidents in UAV operations are mostly related to human error. A better analysis reveals that many of these human errors stem from deficiencies in the interfaces between man and machine [4]. One of the problems introduced by the separation of vehicle and operator is the delay inherent in transmissions between man and machine. While the delay of a line-of-sight data link is negligible, the satellite connection, necessary in some conditions such as operation in a remote area, introduce delays of the order of seconds [1].

The delay period varies from a minimum value close to 100 ms for line-of-sight connections to more than 1600 ms when using geostationary satellites, an amount that it claims to be conservative [5].

Literature and aeronautical regulations indicate that delays greater than 100 ms tend to affect human performance and that delays with a period of 250 to 300 ms can be considered as limiting values [5]. The effects of latency can include loss of situational awareness, an increase in mental workload, and an overall decrease in the effectiveness and efficiency of the human-machine system [6]. This delay is not only caused by large distances, but also by factors related to electronics, encryption, compression, error correction, synchronization, and computations related to the data link [7].

Having explained these harmful effects on controllability, manual control of the aircraft is avoided, making use as much as possible of the levels of on-board automation. For landing operations, for example, it is customary to have a local pilot, resigned to negligible latency, or an automatic landing system. These features, however, may not be available in all conditions, especially in emergencies where a manual landing may be necessary [8]. Despite the existence of the problem, it is noted that the operators of this type of equipment are trained in a simulator to mechanize the landing a few seconds in the future without prediction aids [4].

Added to the delay, there is a difference in piloting due to the absence of vestibular sensitivities. A more detailed description of the unique characteristics of UAVs and their implications for human factors can be found at [9].Thus piloting a UAV is defined as apprehensive because of the use of only one of the five senses available in the human body [4]. The pilot cannot hear the engine, smell the fuel vapors from a leak, taste the acrid smoke of an electrical fire, and feel the sensations of motion, vibration, acceleration, and deceleration [4]. When flying a UAV the vision must accommodate all sensitive needs. Furthermore, the sense of sight is transmitted by only one front camera with a narrow field of view, quite different from human binocular vision. As a consequence, visualization lacks three dimensions, depth perception, and peripheral vision [4].

Despite advances in systems automation, teleoperation will continue to be used, at least as a reserve resource in autonomous missions [6]. Since many UAV accidents can be attributed to human errors and communications delays have been identified as the main contributing factor to these errors. This defines the need to make controlling a UAV with long command delays easier, taking into account the pilot's sensory limitations [8].

1.1 Theoretical Reference

Most of the negative effects of delay can be mitigated by presenting operators with predictive displays, indicating a simulated state of the system [6].

The use of a Head-up Display (HUD) with a predictive algorithm for docking operations of space vehicles is investigated in [10], obtaining positive results for the use of such equipment. In [11], the uses of predictive displays in this type of operation are also investigated, with delays of up to eight seconds, concluding that the predictive control helped operators in their tasks. Already [12], tested predictive controls in docking operations by teleoperation in a simulator, concluding that they increase the accuracy of the procedure.

A comparison between two Micro Air Vehicles (MAV) trajectory tracking techniques is presented in [13], the Linear Model Predictive Controller (LMPC) and Nonlinear Model Predictive Controller (NMPC) techniques, concluding that the second model presents superior results when following aggressive trajectories and under external perturbations.

Finally, [6] developed a predictive trajectory display for a rotary wing UAV to perform vertical takeoffs and landings. The algorithm, however, treated the aircraft model and the system of control as unknown. The objective was to develop an adaptive human-machine interface, capable of being used in different equipment. The system, however, was considered unsuitable for use, concluding that it is necessary to know all the physical properties of the vehicle along with its dynamics.

1.2 Objective

This research seeks to present an experiment that aims to analyze the influence of the communication delay on the pilot's workload when operating a UAV, subject to the delays of a communication link via satellite. The development of the project was defined by the survey of factors, the response to be analyzed, and the selection of the most appropriate design for the experiment.

A UAV operating maneuver was selected as the region of interest. The selection consists of the lateral deviation landing maneuver. The lateral deviation landing consists of a precision landing with lateral correction in a confined space defined by limitations in the virtual environment. This configuration and the experimental test are part of a larger project called Air Domain Study (ADS), where we use a design-test-analyze protocol. The tests were implemented in a simulated environment called ADS Simulator.

2. ADS Simulator

The ADS Simulator is a computerized station developed to reproduce an aircraft model in a flight simulation environment. The dynamic model of the aircraft used for the experiment was developed in Matlab/Simulink software, with all inertial and aerodynamic modeling arrangements, the graphical interface for displaying the scenario, 3D model of the aircraft, and items used during the experiment are generated in the FlightGear software. The Unity software is used to develop a secondary interface that receives data from Matlab/Simulink to show the pilot a predictive trajectory of the movements that will be executed after the delay period in the communications of the links used in scenarios of real flights.

2.1 Graphic Environment

For the experiment, a scenario was created in a way that the pilot will have to land a UAV at an airport outside the aircraft's standard operating zone, performing a lateral correction maneuver with and without communication delay, Figure 1. The entire trajectory is marked with green rings for the pilot to pass through the center, see the Figure 2.

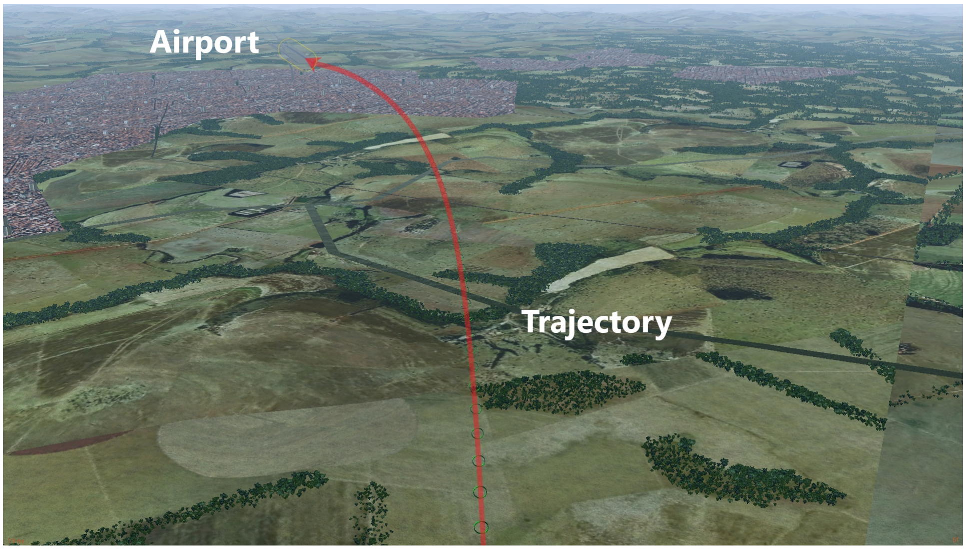

Figure 1 – Mission trajectory.

An attitude prediction interface was developed in Unity software to assist the pilot while there is a delay between the control station and the UAV, this simulation could be an example of control via satellite link. The interface without the aid of prediction can be seen in Figure 2, and the interface with the assistance of prediction can be seen in Figure 3.

Note that the interface of Figure 2 displays the standard data of a HUD, such as speed on the left side, altitude on the right side, the artificial horizon in the center, and heading at the top.

Figure 2 – HUD without interface prediction.

In Figure 3, with the addition of the help interface with prediction data, the pitch angle is displayed on the right side, and the roll angle on the left side, both in numerical format. The clockwise or counterclockwise movement of the green balls on the left side represents the angular speed of rolling, on the other hand, the green ball on the right side can move up or down representing the angular speed of the pitch. The three blue squares represent a resulting attitude prediction, that is, the representation of the two angles mentioned above, but with the addition of the predicted speed data that creates the separation movement between them. It is worth adding that the farthest square is synchronized in the GCS time while the intermediate square is synchronized in an intermediate time and the closest square is synchronized in the aircraft time.

Figure 3 – HUD with interface prediction.

The architecture of data transfer between the applications of the prediction interface is demonstrated in Figure 4, in which the variables of the predicted model related to the interface developed in the Unity environment are transmitted from the model in the MatLab/Simulink environment via User Datagram Protocol (UDP).

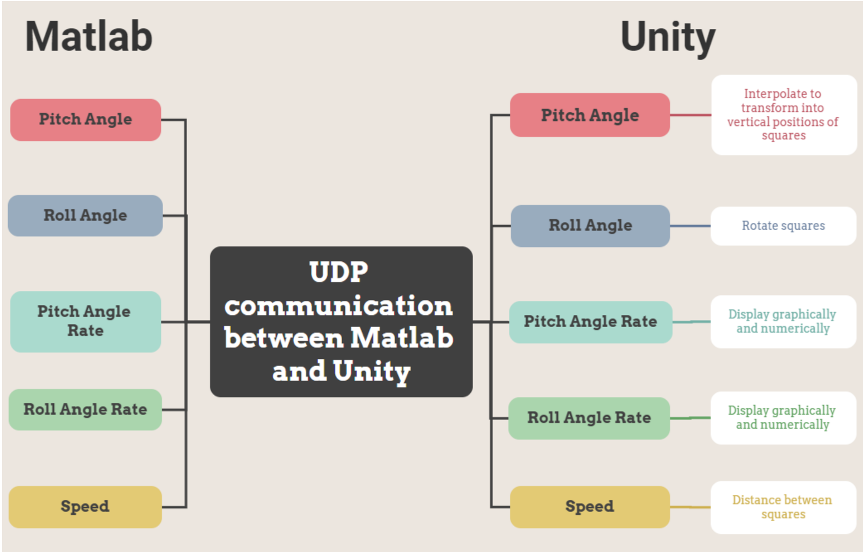

Figure 4 – Communication diagram.

2.2 Control Interface

The control interface was implemented in the MatLab/Simulink environment due to the ease of interconnection with the data from the dynamic model of the aircraft, with the interfaces available in the library, the instrument panel of the aircraft was created, shown in the Figure 5. In the interface, it is possible to notice that the markers of airspeed, vertical speed, heading, engine rpm, altitude and two artificial horizons are implemented, one with data in the aircraft time, that is, with delay and the other with the prediction in actual time from the control station. Together in the interface it is also possible to notice indicators that show the displacement of the aircraft in meters from the center of the trajectory determined for the experiment.

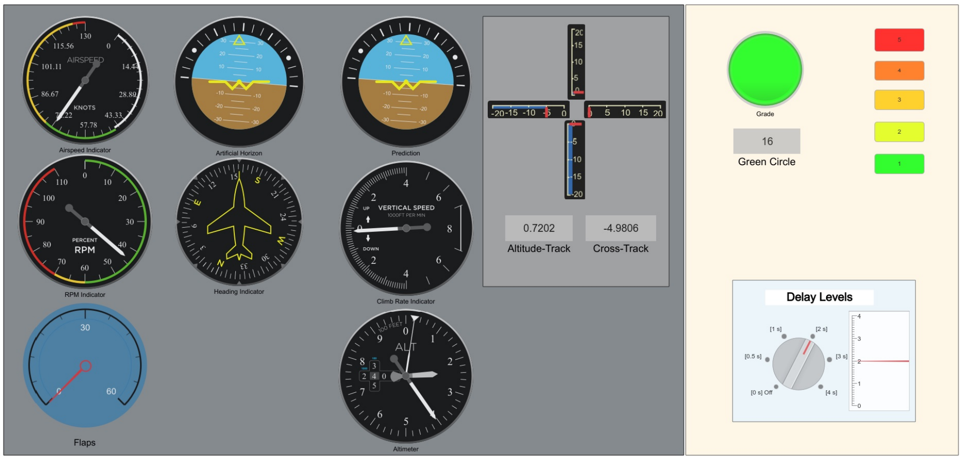

Figure 5 – Control interface.

On the right side of the control interface, it is also possible to observe the delay control adopted in the simulation and the effort classification buttons according to the Instantaneous Self-Assessment (ISA). Which will be detailed in the next sections.

3. Experimental Design

In the experiment, some scenarios were created to analyze the pilots' mental workload. The scenarios were constructed to impose rising levels of task load, and to verify whether the expected mental workload could be discriminated by physiological sensors and subjective questionnaires. For that, 5 scenarios were built: The first is an ideal scenario (A), in which there is no delay in the command, the second scenario contains a delay of 2-seconds in the command of the UAV (B), and the third scenario

a delay of 4-seconds (C). The fourth scenario contains a 2-second delay along with the prediction interface (D), and finally, the fifth and last scenario contains a 4-second delay with the prediction interface (E).
When using the predictive interface, the hypothesis to be evaluated is the decrease in workload within a given task when comparing the different scenarios.
To evaluate and validate the hypothesis, the data collected during the experiment will be subjected to statistical analysis, in which we use the Balanced Latin-Square Design (LSD), which works as a $2nxn$ matrix, to ensure that the number of sequences between treatments is balanced, due to the odd number of scenarios [14].
During the experiment, a within-subject design was used, so the individual difference among the pilots does not influence the results. The experiment allows for a simulation, which consists of 5 simulation rounds, which, to tend to the Latin square, were carried out in a completely randomized way between the pilots, Table 1 shows the treatments, and their assignment to each pilot. This arrangement of the experiment also helped to block the learning effect during the experiment.

Table 1 – Description of the randomized experiment.

Treatments	Cod	Pilot	Order Assignment
Normal	A	1	A,B,E,C,D
Delay 2s	B	2	E,D,A,C,B
Delay 4s	C	3	C,D,B,E,A
Delay 2s - pred	D	4	B,A,C,E,D
Delay 4s - pred	E	5	E,A,D,B,C
		6	D,C,E,B,A
		7	B,C,A,D,E
		8	A,E,B,D,C
		9	D,E,C,A,B
		10	C,B,D,A,E

4. Physiological sensors

Physiological sensors were used to measure mental workload changes among scenarios. Electrocardiogram - ECG, and Galvanic Skin Response - GSR were used.
The ECG is a sensor used to collect electrical signals that are generated from the beating of the human heart. When someone engages in some activity, both physical and mental, it can affect the rhythm of the heartbeat, so the ECG Sensor allows us to recognize the level of these heartbeats and is also used to understand the psychological state of humans. The ECG sensor is placed on the person's chest, in front of the heart.
The most common measure of a GSR signal is not resistance, but skin conductance. Strong emotions can cause stimulation of the sympathetic nervous system, which results in an increased level of sweat being secreted by the sweat glands. Measuring skin conductance due to moisture, pilot sweating, translating the effect of a “surprise event” on workload per sweating in the course of the experiment. The GSR is placed in the pilot's left hand, with the sensors on the index and ring fingers [15].
To analyze the data, there is currently more than one method, and software, such as MatLab, Python, and Kubious [16]. In this experiment PyHRV library of Python was used. Within the analysis performed by the software, some variables are used to analyze the workload index; such parameters are presented in Table 2.

Table 2 – Main parameters used in ECG analysis.

Parameter	Description	Unit
HR	In general heart rate parameters (min., maximum, mean)	bpm
SDNN	The standard deviation of NN intervals	ms
LH/HF	The Ratio Between the LF and HF Components	-

5. Performance Measures

The performance of each pilot within the simulation was determined by reference points in the center of the trajectory, where if the aircraft flies in the center of the green circle the errors in relation to the trajectory will be zero. This is as the pilot moves away to the side of the trajectory, the lateral error increases in meters, in the same way, if the aircraft goes up or down, we will observe the longitudinal error of the aircraft in relation to the center of the trajectory increasing. Thus, it was possible to measure the performance with which the pilot can maintain the trajectory within the simulation environment. The green circles that mark the trajectory can be seen in Figures 2 and 3.

To obtain the pilots' physiological data, the ECG and GSR physiological sensors will be used on their bodies, which will remain until the end of the simulation, to capture the signals throughout the process, which at first has an estimated duration of one and a half hours, in which it is divided between the time in which the pilot will run the simulation.

In addition to the sensors and data analysis software, the Instantaneous Self-Assessment (ISA) was used to analyze the subjective perception of the pilot´s mental workload. ISA has 5 discrete levels, ranging from 1 to 5, indicating the level of instantaneous workload. (1- minimum; 5-maximum). The ISA data will be collected during the experiment, where a grade will be charged, referring to the workload that the pilot is feeling at the moment. Pilots were queried every 30 seconds to grade the workload [17].

Another tool used in conjunction with ISA is the NASA Task Load Index (NASA-TLX) , which is a multidimensional scale designed to obtain performance estimates of one or more operators while they are performing a task, also seeking to demonstrate not only performance but also, workload, which is a term that represents the cost of fulfilling mission requirements for the human operator. To be able to measure the workload, NASA uses some factors that will be evaluated during the task, namely: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration Level, these factors help when measuring the pilot's performance during the process.

Still referring to NASA-TLX, a study was carried out by [18], in which he evaluated more than 500 studies related to NASA, and this study shows that in the evaluated studies 31% focused on the analysis of new interfaces visual displays and/or hearing aids, and 14% of the studies focused on activities directly related to flight, in addition to mentioning that most studies included performance measures and the use of physiological sensor measures [18].

6. Experiment

The experiment was structured as follows, first, a briefing is carried out with the pilot, explaining the purpose of the experiment, the equipment used during the simulation (tabletop simulator, sensors, and analysis methods), and how the simulation would be structured, together with signing the consent form. After the briefing, training on the experimental setup, in order for the pilot to be capable of maneuver and piloting the UAV in an easy and comfortable way. The training focuses on reducing the learning effects during the simulation, a problem that was noticed in the first tests carried out, the training was performed in the conditions without delay and with 3 seconds of delay. Then, the physiological sensors are placed on the pilot, along with data collection for the first baseline while the pilot responds to google forms and the NASA-TLX pair comparison, referring to the training that will serve as a means of comparison to the others. scenarios and soon after we start the simulation. Google forms are intended to ask if the pilot is anxious, how many hours of sleep he has had, and if he feels tired, among other information, since this information can directly affect his performance during the experiment, the structure of the experiment can be seen in Table 3.

Table 3 – Experiment description

Action	Time
Briefing and Signing free consent form	10 min
Training	20 min
place sensors	5 min
Baseline/Pre-flight Questionnaire	5 min
First simulation block	8 min
Post Flight Questionnaire and NASA TLX	5 min
Second simulation block	8 min
Post Flight Questionnaire and NASA TLX	5 min
Third simulation block	8 min
Post Flight Questionnaire and NASA TLX / Second Baseline	5 min
Fourth simulation block	8 min
Post Flight Questionnaire and NASA TLX	5 min
Fifth simulation block	8 min
Post Flight Questionnaire and NASA TLX	5 min
Final Baseline	5 min

The data collection to form the pilot baseline worked as follows, 3 baselines were collected. The first baseline was collected when the pilot arrived at the experiment site, the collection took place after the pilot briefing and training, the second baseline was collected in the interval between flight 3 and flight 4, and the final one was collected when the experiment ended, after the last flight. The best baseline to use for comparing the data obtained is the third one since the pilot will be relaxed to complete the task, without having the pressure or anxiety to do something affecting the data, which happens when we look at the first and second baselines collected[19]. Figure 6 exemplifies how the tests took place, it is possible to notice the sensors in the pilot's left hand.

Figure 6 – Pilot in the simulation.

After the end of each simulation, it is necessary to answer the NASA-TLX, in which the mental workload in each simulation will be evaluated.
Then the execution of the complete simulation, running the experiment with 10 pilots, we were able to create a database, which made it possible to analyze the experiment, containing all the data obtained in this process. As the purpose of the experiment was to evaluate the workload during the route, the pilots were not charged to land the UAV, thus arriving at a certain area close to the landing to validate the data.

7. Results

It is described in Table 4, which pilots managed to land the UAV, the table contains the code referring to the pilot together with the randomized flight that he performed, in the columns referring to the different scenarios we can see if the pilot landed the UAV or not, the fully completed flights were used the abbreviation "C" to define that the UAV was landed, for those who managed to land, but were not able to on the first attempt, the abbreviation "C" was used together with the attempt number that the pilot managed to land, and for pilots who were unable to land, but arrived in the area delimited as a minimum area for data validation, the acronym “NC” was used.

Table 4 – Pilots and flights

CODE	FLIGHT	A	B	C	D	E
2	2	C	C	N/C	C	C/3
3	3	C	C	C/2	C	C
4	4	C	C/2	C/2	C	C/3
5	5	C	C	C	C	C
6	6	C	C	NC/2	C	NC/2
7	7	C	C	C	C	C
8	8	C	C	C	C	NC
10	1	C	C	C	C	C
11	9	C	C	C	C	C
12	10	C	C	N/C	C/2	C/3

With the database collected, it was possible to perform the statistical analysis, using LSD method. In Figure 7, it is presented the boxplot of the test results ANOVA for HR, SDNN, LF/HF, and GSR data.

- Time Domain - HR

  In the HR time domain, based on the results obtained for the HR, it appears that it was not possible to discriminate the different treatments (experimental conditions) (P(>F) = 0.166). As shown in the Boxplot of Figure 7, it appears that the average of the values of condition C - delay-4s tends to be higher than the others, as expected, but without statistical confirmation.

- Time Domain - HRV - SDNN

  In the HRV - SDNN time domain, based on the results obtained, it can be observed that the SDNN ratio between treatments A-E is not statistically significant (P(>F) = 0.177606 The analysis, however, showed a significant statistical difference between the pilots (P(>F) = 0.000398).

- Frequency Domain - LH/HF

  In the LF/HF, it appears that it was not possible to discriminate the different treatments (experimental conditions) (P(>F) = 0.64792). As shown in the Boxplot of Figure 7, it appears that the average of the values of condition C-delay-4s tends to be higher than the others, as expected, but without statistical confirmation. The analysis, however, showed a significant statistical difference between the pilots (P(>F) = 0. 0.00238).

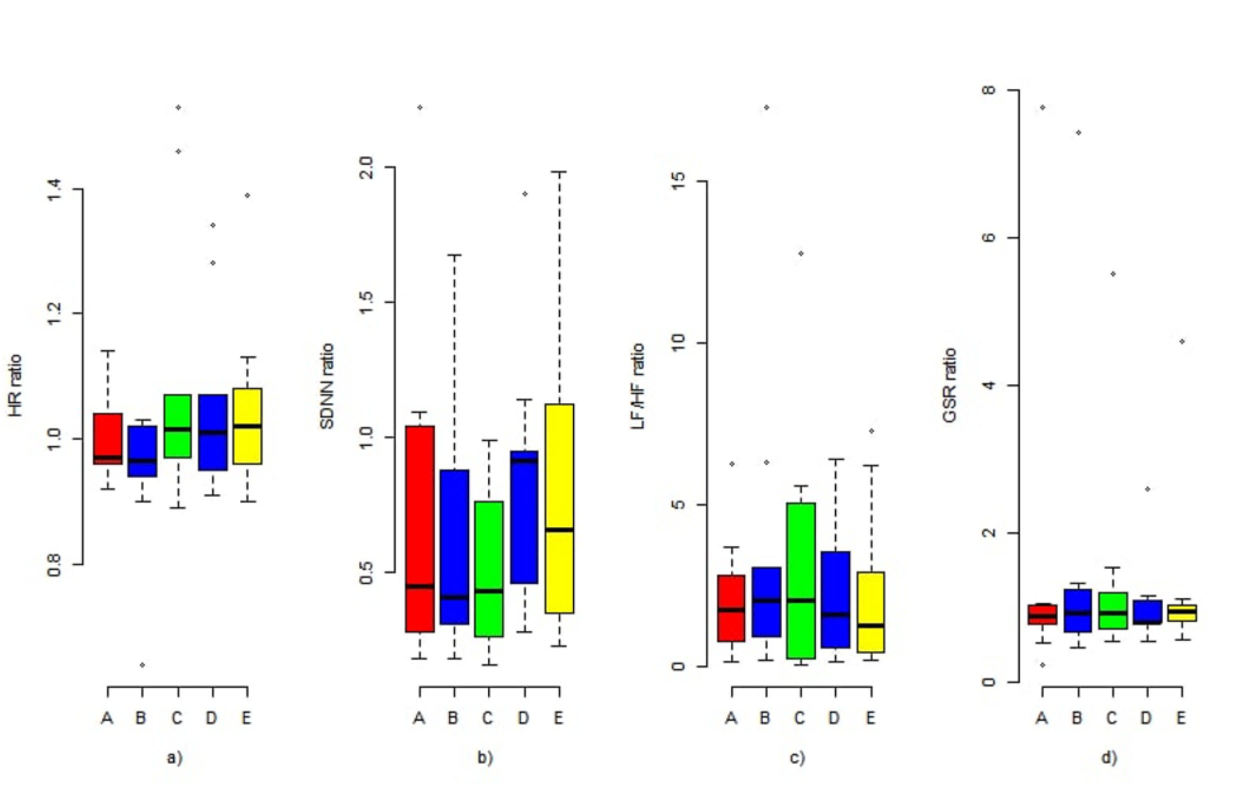

Figure 7 – ANOVA–HR, SDNN, LF/HF, and GSR data.

- GSR

  In the GSR, it appears that it was not possible to discriminate the different treatments (experimental conditions) (P(>F) = 0.527). The analysis, however, showed a significant statistical difference between the pilots (P(>F) = 3.44e-12).

In Figure 8, the boxplot of the ANOVA test results for the Global Performance, NASA-TLX data, and the ISA test medians is presented.

- Global Performance

  Based on the results obtained for the Global Performance, it can be verified that it was possible to discriminate the different treatments (experimental conditions) (P(>F) = 0.012). As shown in the Boxplot of Figure 8, it can be seen that the average values of the conditions C-delay-4s and E-delay-4s with interface tend to be higher than the others, as expected, with statistical confirmation. The analysis, however, did not show a statistically significant difference between the pilots (P(>F) = 0.854). To confirm the treatment analysis, a Tukey test was performed, which showed that treatments C-B and D-C differ.

- NASA-TLX Subjective Assessment

  Based on the results obtained for NASA-TLX, it can be seen that it was not possible to discriminate the different treatments (experimental conditions) (P(>F) = 0.474). As shown in the Boxplot of Figure 8, it can be seen that the mean values of condition C - delay-4s and E - delay-4s with interface tend to be higher than the others, as expected, but without statistical confirmation.

- ISA

  Based on the results obtained for the ISA, it can be verified that it was possible to discriminate the different treatments (experimental conditions) (P(>F) =7.60e-10). As shown in the Boxplot of Figure 8, the ISA was extremely selective, identifying different levels of mental load across all conditions, as expected, with statistical confirmation. The analysis showed a statistically significant difference between the pilots (P(>F) = 1.36e-05). To confirm the treatment analysis,

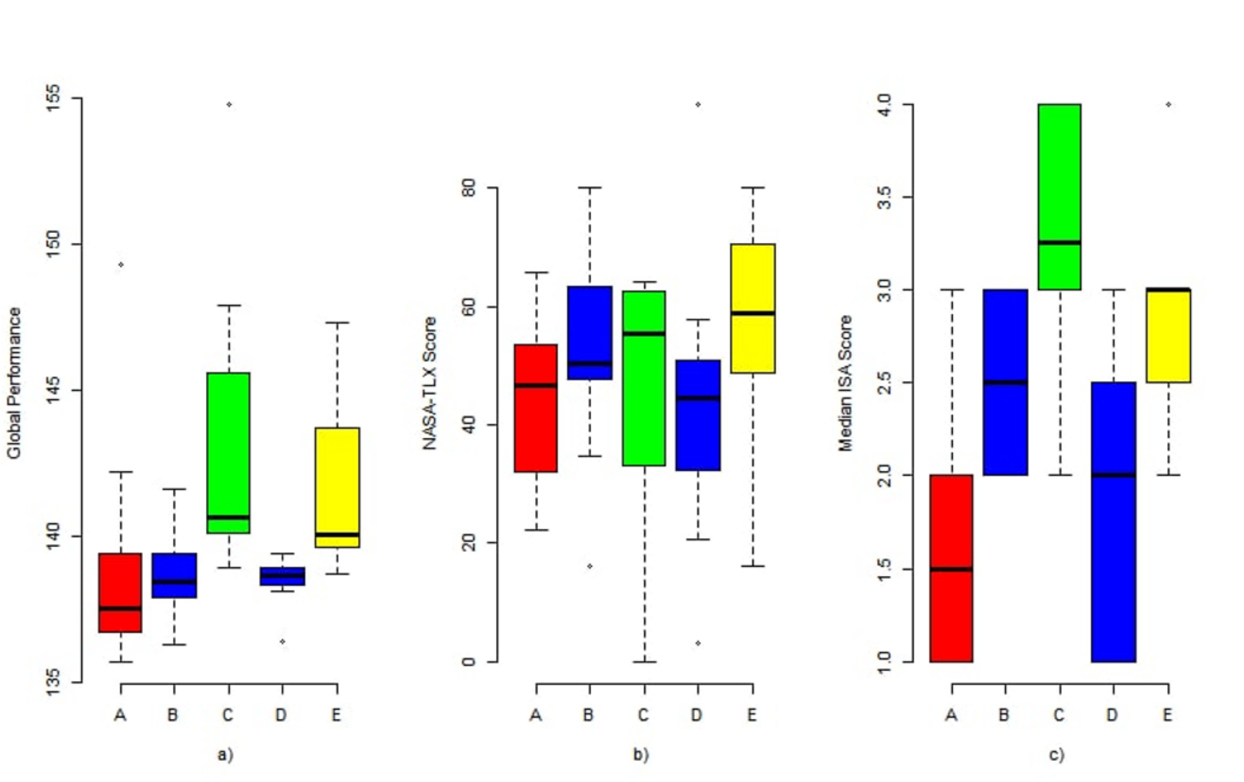

Figure 8 – ANOVA–Global performance, NASA-TLX data, and the ISA test medians.

a Tukey test was performed, which showed that treatments B-A, C-A, E-A, C-B, D-C, and E-D differ.

8. Conclusions and Future Works

This experimental setup and trials are part of a more comprehensive project entitled Air Domain Study - ADS, where we use a design-test-analyze protocol. This preliminary experiment trained all the laboratory staff in designing an experiment, integrating different software to allow further research on UAV and Human Factors related issues. Considering that, we achieve the proposal of implementing the experimental setup. Specific results obtained showed that physiological sensors could not discriminate mental workload, as task load (delay and predictive approach) increases. Neither NASA-TLX, a well-known, subjective tool was able to do that, but ISA, which was developed to be used in Air Traffic Control - ATC context performed well in discriminating different levels of perceived workload. Further research will be accomplished in order to better comprehend physiological sensors' sensitivity in UAV scenarios.

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11. Copyright Statement

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