OPERATORS (PILOTS, ATCOS)’ LOAD MONITORING 
AND MANAGEMENT

A Dissertation submitted by:

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Summary
The revolution in information, computer, navigation and communication technologies catalyse to development of large highly automated systems in operators’ (Pilots, Air Traffic Controllers- ATCOs) environments, such as future aviation systems. In parallel to these rapid technological changes, a large number of aerospace companies, universities, and institutes have been initiated intensive research on the future of autonomous systems. Worldwide several mega international and national projects have been initiated for the research, development and implementation of systems, regulations and procedures for future aviation systems such as SESAR [1], and Next-Gen [2]. One of their main objectives is to bring an extensive range of innovative solutions [3]; [4]; [5] to the current and future aviation issues to cope with growing air traffic, under the safest [4]; [7]; [8] and environmentally friendly conditions; [9]; [10]; [11]. These investigations have been introduced to countless technological and system innovations in operators’ working environments [6]; [12]. The aviation industry has already come a long way, but the efforts are and will be never enough. There have been rapid and significant changes in aviation technologies in recent years. Thereby the level of automation, aviation systems and the working conditions of the operators are continuously changing and being redesigned [13]. Aviation operations, therefore, must continue to adapt respectively and meet the needs of the growing aviation industry. In a continually changing world, the role of operators, namely pilots (on-board and remote) and ATCOs, are in transition from active endogenous control to passive monitoring due to the introduction of the intensive automation. This means before operators were actively taking part in the controlling process, however now they are in a position of monitoring the current system. During active control, the operator simultaneously is involved in a series of actions (situation awareness – decision making – control actions) while automated systems, the operator monitors the operating system and only in abnormal and/or an emergency situation operator should engage active control [14]; [15]; [16]. With continuous evolution of the flight systems, including aircraft capabilities, radar, and sensor systems, operators are supported by vast amounts of available data and relevant information. In this current modern operator environment, the role of the operator became an information manager than an operator instead. Available too much information confuses operator during operation, particularly while decision-making time in abnormal/emergency situation. In parallel with these changes, operator load systems have been significantly changed as well. This highly automated system may be accompanied by unbalanced operator load systems (vary from under load to overload), unintended reductions in situation awareness, decrease in the quality of decision-making, increased the level of stress. The future operator environment (cockpit, future ground control tower of pilots, air traffic control towers) needs to be redesigned by taking into account various psychological parameters, human factors and operator loads.
The main objective of this thesis is to develop general load monitoring and management systems of operators working in highly automated systems. Therefore, the sub-objectives (tasks to be performed) of this study are in fourfold: first, to develop operator load models for pilots and ATCOs, second, to develop concept of load measuring systems, to create some sensors and performing test measurement, third, to investigate some special aspects that influence safety like misunderstanding of communication systems and last, build operator load management systems by using the measurement.

**Thesis Content**

This thesis aims at building load monitoring systems in operators ‘working environments and managing their total loads. To achieve this, four chapters were designed in this thesis. In the first chapter, the role of operators in future aviation systems was described, such as operators’ roles, working environments, human factors and model. In the scope of the SESAR project, the real data from the validation exercise were used in testing the dynamic sectorization method [17]. In the second chapter, several well-known operator models were studied and adapted to the human operator work in highly automated systems, such as Endsley “load model” [18], Rasmussen “situation awareness and decision-making model” [19], Kasyanov “subjective decision model” [20], and Wickens “information model” [21]. The role of mental condition was found to be increased in highly automated systems, and task and workload become more interconnected, and information load and communication load were detected as a new type of operator loads. Thereby a new operator load model was created and divided into five categories, namely work, task, information, communication and mental load [14]. The created generalised model was used in developing the ATCOs environment [22]; [23]; [24] and less skilled pilot support [22]; [23]; [25]. The subjective decision-making of the different level of experience of pilots, namely (i) student pilot, (ii) less-skilled pilot, (iii) experienced pilot and (iv) well-experienced, were modelled on Matlab by the modified Lorenz attractor (Figure 4). During the final approach, „hesitation frequency” and „decision-making time” were calculated for landing and go-around situations. In addition to this, some unique aspects of operators were investigated in this chapter which influence on safety like misunderstanding. A questionnaire was conducted to 212 operators (168 ATCOs and 44 pilots) in order to investigate the reasons for communication errors, avoid pragmatic failure and minimise the risk of misunderstanding of operators (pilots, ATCOs) related to several factors such as cultural norms, social relations, regional accents and poor language skill. Once the areas of pragmatics and other possible linguistics sources of misunderstanding and their impact on air safety have been identified. Some approaches were proposed for native and non-native English speaking operators, and also for both to improve their aviation communication particularly via the radio-telephony communications [26].
In the third chapter, the load monitoring systems was developed and the measurements were performed such as eye-tracking [7]; [14]; [23] integrated microsensors and motion cameras [14]; [15]; [27], heart rate [7]; [14]; [23], and (iv) EDA (Electrodermal Activity) measurement [7]; [23]; [27]; [41]. In the fourth chapter, operator load management systems were built by using the measurements. Two different variety of total load management methods were defined based on workload, task load, information, communication and mental load for overload and underload situations: (i) assign a scoring method - say in [0,1] to all the measurements and (ii) mathematical modelling [23]; [28]; [41]. Finally, the summary, major results, theses, and recommendations for the future works were presented.

**Major Results**

- Several well-known operator models were studied and adapted to the human operator work in highly automated systems, such as Endsley “load model” [18], Rasmussen “situation awareness and decision-making model” [19], Kasyanov “subjective decision model” [20], and Wickens “information model” [21].

![Diagram](https://via.placeholder.com/150)

*Figure 1: The created model of situation awareness and decision making in future dynamic ATM environment (Source: Own Modified Edition [14]; [22]; [23])*

- The role of mental condition was found to be increased in highly automated systems, and task and workload become more interconnected, and information load and communication load were detected as a new type of operator loads. Thereby a new operator load model was created and divided into five categories, namely work, task, information, communication and mental load (Figure 2).
The research was done on developing a working environment enhanced with integrated sensors to collect information on operators’ activity, thereby increasing situational awareness, the quality of decisions and balance loads on the subject. By analysing the test results, the applied methodology showed that the developed system could be applied in the pilot training [14], ATCOs’ working environment [29], and as well as car drivers’ environment [30]; [41].

TOBII eye-tracker has been used to record the visual patterns of the pilots through an engine failure scenario. By analysing the result of the operator eye-movements, eye-tracking systems can be a useful tool for pilot and ATCO training.

The integrated motion cameras defined eye movement and the area of interest of pilots through three flight scenarios. Eye movements are very depending on the task, experience, and human behaviours. A strong relation found between task and operator working behaviours like during taxi, take-off and landing (experienced
and less-skilled pilots) [14]; [15]; [41]. Based on the eye movement results, the less-skilled pilot makes more eye movements during taxi (35%), take-off (37%) and landing (41%) compared to experienced pilots [41].

- The complexity of the task is directly proportional to the number of eye movement per second. In other words, if the complexity of task increases, the number of eye movement (per second) also increase, respectively. Concerning this, the number of eye movement of the experienced pilot is (i) 1.31 per second under Visual Meteorological Conditions (VMC) scenario, (ii) 1.82 per second under Instrument Meteorological Conditions (IMC) scenario, and 2.38 per second under IMC with Attitude Directional Indicator (ADI) failure [41].

- The number of eye blink (full blink and half blink) of experienced pilot increased significantly in parallel to the task complexity: (i) 0.25 per second under Visual Meteorological Conditions (VMC) scenario, (ii) 0.29 per second under Instrument Meteorological Conditions (IMC) scenario, and 0.39 per second under IMC with Attitude Directional Indicator (ADI) failure [41]. In addition to this, it is also noticed that eye flutters (rapid muscle movement in the eyebrow area) also increased.

- The subjective decision-making of the different level of experience of pilots, namely (i) student pilot, (ii) less-skilled pilot, (iii) experienced pilot and (iv) well-experienced, were modelled on Matlab during final approach by the modified Lorenz attractor. According to the results, the “decision-making time” and “hesitation frequency” are increasing while the level of experience is decreasing. This model is well usable for the investigation of the decision-making process of pilots from different skills and experience. This method improves pilot training and helps instructors to understand the weaknesses of pilots better as well. During the final approach, the less-skilled pilot requires about six times more time for making the final decision on go-around than the well-practised pilot. These results demonstrate that the model is suitable to investigate the different level of pilots while checking their way of thinking and decision-making process.

![Figure 4](image_url)

**Figure 4: The results of the developed model: General 3D view (left) and the decision-making process for go-around (right) (Source: Own Edition)**
• I have defined how to interpret operator measured heart rate depending on the situation (flight scenarios and traffic situation). A strong relationship found between the complexity of the task and heart rate of pilots. The heart rate of the pilot is significantly changing on the complexity of task scenarios: (i) Average Heart Rate: 82,4 bpm- Standard Deviations (SD): 10,8- Root Mean Square (RMS): 83,1) under Visual Meteorological Conditions (VMC) scenario, (ii) Average Heart Rate: 96,8 bpm- Standard Deviation: 6,95- RMS: 97,0 under Instrument Meteorological Conditions (IMC), and (iii) Average Heart Rate: 103,9 bpm- Standard Deviation: 6,98- RMS: 104,1 under IMC with Attitude Directional Indicator (ADI) failure scenario. Based on the results, it can be also found that If the complexity of the task is increasing, the average of the heart rate is also significantly increasing. I found that the heart rate variability can be used as a major indicator for detecting the mental load that even may indicate the task complexity monotony and the ratio of automation (Figure 5).

![Figure 5: Comparison of operator heart rate through the scenarios (Source: Own Edition [7]; [14]; [23])](image)

• The Skin Conductance Level (SCL) of a pilot was recorded by OBIMON devices (an Electrodermal activity-EDA device) during all phases of the flight through “a poor visibility and instrument failure” flight scenario. The results suggested that emotional arousal was highest during flight take off in comparison to en-route and landing. In addition to this, based on analyses of the measured EDA, the arousal was found to be high, when the flight took turns (Figure 6, [7]; [23]; [27]; [41]. According to the results, the actual mental condition can be estimated, which means, it is possible to determine if an operator is tired, unbalanced loaded (overloaded or underloaded) or nervous at the moment.
I was taken part of a SESAR project dealing with airspace design and dynamic sectorization on the evaluation of the verification and validation of the results. I was detected that the task load, as defined by NASA - TLX, can be managed by defined airspace design and dynamic sectorization, and I found that the dynamic sectorization and air space configuration may eliminate the task overload and reduce the actual load by 30-40 per cent [17].

Operator load index calculation method was defined by the current researcher, by the following formula [41]:

\[ i_{Load} = \sum_{i=1}^{5} w_{ei}(u, z) L_c \]

where \( i_{Load} \) is total load index, \( w_{ei} \) is weighting coefficient and \( L_c \) is the load coefficient, \( u \) is the control and \( z \) is the environmental characteristics.

\[ i_{Load}[k + 1] = \sum_{q=1}^{r=9} (A[k]i_{Load}[k] + w_{qu}B[k]u[i_{Load}[k]] + w_{qz}F[k]z[k]) \]

when \( u[k, i_{Load}[k]] \) is the management definition and \( z[k] \) is the environment. \( u_1 = \) Work load, \( u_2 = \) Task load, \( u_3 = \) Information load, \( u_4 = \) Communication load, \( u_5 = \) Mental load and \( z_1 = \) Structure (such as mechanical failure, malfunction of the automation system or software errors), \( z_2 = \) Pilots, \( z_3 = \) ATCOs, \( z_4 = \) Surroundings (such as normal or severe weather condition) [41].

Figure 6: Skin conductance level of a pilot during the scenario (Source: Own Edition [7]; [23]; [27]; [41])
- I found that in a highly automated system, large mental load, such as communication overload loads are increasing. According to my investigation, I have recommended to include the English conversation using by different cultural norms and social relations into the pilot and ATCO training [26].
- All the developed load monitoring and management methods were supported by measurements and applied load monitoring in the screen of pilots (Figure 9, [22]; [23]; [25]; [41]) and ATCOs (Figure 10, [22]; [23]; [24]; [41]).

**Figure 9:** Future load monitoring and management design in the cockpit
(Source: Own Edition [22]; [23]; [25]; [41])

**Figure 10:** Future load monitoring and management design in the ATM
(Source: Own Edition [22]; [23]; [24]; [41])
New Scientific Results

Statement I:

I have investigated and analysed the role and load of the human operators (Pilots and ATCOs - Air Traffic Controller) working in highly automated, complex, active, endogenous, ergatic, technogenic systems¹ including investigation of the operator situation awareness – analysis – decision-making process by using (i) outside measurements, like motion camera [U.K.1]; [U.K.2]; [U.K.8]; [U.K.11], and eye-tracking [U.K.1]; [U.K.2]; [U.K.3]; [U.K.10]; [U.K.17], (ii) microsensors integrated into working environment (like skin resistance, and skin temperature sensors integrated into computer mouse, and side stick [U.K.1]; [U.K.2]; [U.K.6]), (iii) connecting directly to the operators body: heart rate/heart rate variability [U.K.1]; [U.K.2]; [U.K.3]; [U.K.17], ECG, EEG, EMG, EDA-Electrodermal Activity [U.K.1]; [U.K.3]; [U.K.10]; [U.K.11]; [U.K.17], and sensors integrated into operator clothes [U.K.22], and (iv) adapting simulation methods like using the method of subjective analysis (Figure 4).

Thesis I:

I had discovered three phases of operator working behaviour in highly automated systems as „stage fright”, moderate load, and overload/underload.

• The first mode, „stage fright” is the beginning of operation determining by attention disappearing due automation trust (like pilot working very well during take-off and relaxing during the climb) [U.K.1]; [U.K.3]; [U.K.10]; [U.K.11]; [U.K.17].

• The second is the „moderate mode” when the operator load index is around 0.4 and 0.5 (operators load index reduces because of the passive monitoring system – en-route phase [U.K.1]; [U.K.6]; [U.K.7]).

• The third is the „overload/underload mode” causes by changing in a situation (traffic complexity increases or system errors appear) or long-time monotony [U.K.1].

• The differences between the modes are raised in reaction time, increasing the time required for situation awareness, analysis decision-making, thereby

¹ Active system, because the operators actively react to the estimates situation. Endogenous system, because the solution is coming from inside of the system. Ergatic system, because operators are element of the system. Techogen system, because the technical and economic systems have a significant influence on the environment.
increasing the reaction time and frequency and amplitude of “hesitation” (Figure 4, [U.K.1]; [U.K.2]).

Statement II:
I have taken part in developing sensors and methodology for monitoring of human operator loads (developed eye-tracking systems, integration of microsensors into operator environment like side stick, and computer mouse). Based on the eye-tracking measurement, I have developed a recommendation for using eye-tracking systems for pilot training in the flight simulator [U.K.2]; [U.K.10]; [U.K.15]; [U.K.20]; [U.K.22]. Moreover, eye movement and the area of interest of pilots (experienced and less-skilled pilots) were defined through three flight scenarios: (i) Visual Meteorological Conditions (VMC), (ii) Instrument Meteorological Conditions (IMC), and (iii) IMC with Attitude Directional Indicator (ADI) [U.K.2]; [U.K.6].

Thesis II:
I have demonstrated by using the created sensors and methodology that the human-machine and operator behaviour can be identified in a form in which required for future system development.

• I found about 30 per cent decrease in the required time for learning the prescribed procedure like take-off and landing in case of using eye-tracking systems during flight training [U.K.1]; [U.K.2]; [U.K.10]; [U.K.22].

• I found a strong relationship between task and operator working behaviours like during taxi, take-off and landing, (characterising experienced and less-skilled pilots [U.K.3]; [U.K.10]; [U.K.17], see pages 4;5).

• I have defined how to interpret operator measured heart rate depending on situations (flight scenarios and traffic situation). I found a strong relationship between the complexity of the task and heart rate Figure 5, [U.K.2]; [U.K.10]; [U.K.13] (see page 6).

• I found that EDA measurements fully support the operator load index classification [U.K.1]; [U.K.7]; [U.K.8]; [U.K.17] (see thesis 1).

• I found (based on the measurement of EDA) that the emotional arousal of the pilot was highest during flight take-off in comparison to en-route and landing. In addition to this, the arousal level of the pilot was found to be high, when the flight took turns (Figure 6, [U.K.1]; [U.K.10]; [U.K.11]; [U.K.17]).
• I found that the investigated measuring methods (eye-tracking, eye movement, heart rate and EDA measurement) fully allow to implement, created by me, load monitoring and displaying systems for pilots (Figure 9, [U.K.1]; [U.K.6]; [U.K.7]; [U.K.10]) and ATCOs (Figure 10, [U.K.1]; [U.K.6]; [U.K.10]; [U.K.23]).

Statement III:
I have studied the well-known operator models like „Load Model” by Endsley, „Situation Awareness Model” by Rasmussen, „Subjective Characters of Decision-Making Model” by Kasioanov, „Information Model” by Wickens, and „Swiss Cheese Model” by James Reason. I have generalised these models and adapted to the human operator work, working in highly automated systems [U.K.1]; [U.K.2]; [U.K.6]; [U.K.26].

Thesis III:
I have improved and adopted Endsley and Rassmussen models by including the human performance, skill, competence and information process that enable fully modelling the operator situation awareness and decision process in highly automated systems.

• I have integrated „Rasmussen Situation Awareness Model” into the generalised model created by using the „Endsley Model” for the description of the working behaviours of the operators monitoring and managing the highly automated systems [U.K.1]; [U.K.2]; [U.K.10]; [U.K.11].

• I have included the „Subjective Decision Model” into the created generalised model (Figure 1, [U.K.2]; [U.K.6]; [U.K.7]).

• I have included human behaviours (skill, competence, knowledge, tacit knowledge) into the created generalised model (Figure 1, [U.K.2]; [U.K.6]; [U.K.13]).

• The created generalised model was used in developing the ATCOs environment and less skilled pilot support [U.K.1]; [U.K.2]; [U.K.13]; [U.K.22].

Statement IV:
I investigated and created a generalised model in simulations, in-flight and ATCO simulators. I found that the role of mental condition is increased in highly automated systems, and task and workload become more interconnected, as well as information load and communication load were detected as new types of operator loads. I was taken part of the SESAR project dealing with airspace design and dynamic sectorization on the evaluation of the verification and validation results [U.K.4]; [U.K.16]. I made a series of measurements by using different
sensors and methodologies (heart rate, EDA, skin resistance, skin temperature, and eye-tracking etc.).

**Thesis IV:**
I created a new operator load model, including five types of loads that were tested and verified in simulators and partly validated in real situations.

- I found that the task load, as defined by NASA - TLX, and workload used by most of the previous researchers, can be applied to highly automated systems as well [U.K.1]; [U.K.2]; [U.K.6]; [U.K.13]; [U.K.22].

- I found that the dynamic sectorization and air space configuration may eliminate the task overload and reduce the actual load by 30-40 per cent [U.K.4]; [U.K.16].

- I found that the role of mental load in highly automated systems is increasing (due to passive monitoring) [U.K.1]; [U.K.2]; [U.K.6]; [U.K.13]; [U.K.22].

- I introduced two new loads into the load model: information load (depending on too much available information which confuses operators), and communication load (affecting by communication intensity) [U.K.1]; [U.K.2]; [U.K.5]; [U.K.9].

- I found that the heart rate measurement can be used as a significant indicator for detecting the mental load that even may indicate the task complexity monotony and the ratio of automation [U.K.10]; [U.K.22].

- I made a recommendation to include the English conversation using by different cultural norms and social relations into the pilot and ATCO training [U.K.5]; [U.K.9].

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**Statement V:**
I was investigated the possible operator (Pilots and ATCOs) load management methods for overload and underload situations.

**Thesis V:**
I created two different variety of total load management methods based on workload, task load, information, communication and mental load for overload and underload situations: (i) assign a scoring method - say in [0,1] to all the measurements, and (ii) mathematical modelling.
• I defined thresholds for each load independently for overload situation as warning signals, calling special attentions (continuously monitoring the operating condition), and immediate actions required, respectively 0.8, 0.9 and 0.95 (according to the defined scoring method) [U.K.1]; [U.K.10]; [U.K.14].

• I defined thresholds for the combination of at least two loads for overload situation, namely in a case when at least two types of load coefficients in any combination, reach to 0.7 or above as warning, monitoring, and immediate actions required, respectively 0.7, 0.8, and 0.9 (according to the defined scoring method) [U.K.1]; [U.K.10]; [U.K.14].

• I defined thresholds for each load independently for underload situation as warning signals, calling special attentions (continuously monitoring the operating condition), and immediate actions required, respectively 0.2, 0.1 and 0.05 (according to the defined scoring method) [U.K.1].

• I defined thresholds for the combination of at least two loads for underload situation, namely in a case when two types of load coefficients in any combination, reach to 0.3 or below as warning, monitoring, and immediate actions required, respectively 0.3, 0.2, and 0.1 (according to the defined scoring method) [U.K.1].

• The following formula defined by the current researcher for the load index calculation method of operators [U.K.1]:

\[ i_{Load} = \sum_{i=1}^{5} w_{ei}(u, z)L_c \]

where \( i_{Load} \) is total load index, \( w_{ei} \) is weighting coefficient and \( L_c \) is the load coefficient, \( u \) is the control and \( z \) is the environmental characteristics.

\[ i_{Load}[k + 1] = \sum_{q=1}^{r=9} (A[k]i_{Load}[k] + w_{qu}B[k]u[i_{Load}[k]] + w_{qz}F[k]z[k]) \]

when \( u[k, i_{Load}[k]] \) is the management definition, and \( z[k] \) is the environment. \( u_1 = \) Work load, \( u_2 = \) Task load, \( u_3 = \) Information load, \( u_4 = \) Communication load, \( u_5 = \) Mental load and \( z_1 = \) Structure (such as mechanical failure, malfunction of the automation system or software errors), \( z_2 = \) Pilots, \( z_3 = \) ATCOs, \( z_4 = \) Surroundings (such as normal or severe weather condition) [U.K.1].
Own References


References


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