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Operators (Pilots, ATCOs)’ Load Monitoring and Management

A dissertation submitted by:
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In Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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Declaration of Authorship

I, Utku Kale, declare that this dissertation titled, “Operators (Pilots, ATCOs)’ Load Monitoring and Management” and the work presented in it are my own. I confirm that:

• This work was done wholly while in candidature for a PhD degree at this University.
• Where any part of this dissertation has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
• Where I have consulted the published work of others, this is always clearly attributed.
• Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this dissertation is entirely my own work.
• I have acknowledged all of the main sources of help.
• Where the dissertation is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

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Acknowledgements

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List of Glossaries

ACERE: Advisory Council for Aeronautics Research in Europe
ADI: Attitude Directional Indicator
ANS: Automatic Nervous System
ASI: Air Speed Indicator
ASRS: Aviation Safety Reporting System
ATC: Air Traffic Control
ATCO: Air Traffic Controller
ATM: Air Traffic Management
BME: Budapest University of Technology and Economics
bpm: Beat Per Minute
CAA: Civil Aviation Authority
CARATS: Collaborative Actions for Renovation of Air Traffic System
CNS: Central Nervous System
DAG-TM: Distributed Air/Ground Traffic Management
EDA: Electrodermal Activity
ELTE: University of Eötvös Loránd
EP: Evoked Potentials
EUROCONTROL: European Organization for the Safety of Air Navigation
FAA: Federal Aviation Administration
FDDRL: Flight Deck Display Research Laboratory
HFACS: Human Factors Analysis and Classification System
HIS: Horizontal Situation Indicator
HR: Heart Rate
HRV: Heart Rate Variability
HungaroControl: Hungarian Air Navigation Services
ICAO: International Civil Aviation Organization
IMC: Instrument Meteorological Condition
INS: Inertial Navigation System
LCD: Liquid Crystal Display
List of Glossaries
LoA: Level of Automation
MAW: Moving Average Time Window
MFD: Multi-Functional Display
NASA: National Aeronautics and Space Administration
NASA-TLX: NASA Task Load Index
Next-Gen: Next Generation Air Transportation System
OBIMON: Open-source Bio-monitor of Electrodermal Activity
Operator: Pilots and Air Traffic Controllers
PID: Pilot Induced Oscillations
PNS: Parasympathetic Nervous System
PPG: photoplethysmography
Rdisp: Disposable Actions
RMS: Root Mean Square
Rreq: Required Actions
RTCA: Radio Technical Commission for Aeronautics
S/PATS: Small/Personal Air Transport System
SA: Situation Awareness
SAGAT: Situation Awareness Global Assessment Technique
SART: Situation Awareness Rating Technique
SATI: SHAPE Automation Trust Index
SCL: Skin Conductance Level
SCM: Swiss Cheese Model
SD: Standard Deviation
SESAR: Single European Sky ATM Research
Si: Situation Process
SIRIUS: Impulsionando o Desenvolvimento do ATM Nacional
SNS: Sympathetic Nervous System
Sp: Possible Actions
SPO: Single Pilot Operation
SRIA: Strategic Research and Innovation Agenda
VFR: Visual Flight Rules
VMC: Visual Meteorological Condition
VRHT: Department of Aeronautics, Naval Architecture and Railway Vehicles
VSI: Vertical Speed Indicator
Abstract

Technological advances in avionics, automation, and computing processes have produced highly complex operator-machine systems and significant improvements. These systems may solve some of the previous problems; however, they often introduce others. With the introduction of advanced automation, operator environments became very automated. While the responsibility of the operator to fly safely remain unchanged, several new skills are required to control aircraft. The future operator environment (cockpit, future ground control tower of pilots and towers) and avionics systems need to be redesigned by taking into account various psychological parameters, human factors and operator loads. As the avionics system became more complex, evaluation of the performance of operators was required, such as situation awareness, decision-making, and operator load. Operators need viable constructs, principles and aviation systems to promote a better understanding of automation and balancing their loads in complex systems. This highly complex and dynamic environment measures operator performance more complicated than the early time of aviation. Despite all the advancements in aviation technology and cockpit automation, aviation accidents continue to occur. With the 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 operators during operation, particularly while the decision-making process in abnormal/emergency situations. In parallel with these changes, the operator load system also has been significantly changed. 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. In this thesis, the operator load model was created and the operator load divided into four categories, namely work, task, information, and mental load. In this thesis, a new situation awareness and decision-making model was created. With the developed system, operators will have tasks according to their current condition, including the level of work, task, and psychological state. Another advantage of the developed load monitoring and management system is, in case of a very high level of load, the control of aircraft will be able to take over from the operators.

This thesis work comprises the evaluation, monitoring, and management of the operator total load systems. In that context, the load monitoring devices developed and used in an operator working environment.
Introduction

Air transportation is expected to continue growing considerably over the next two decades. In dealing with this growth, it is essential to ensure the highest level of safety and security. The revolution in information, computer, navigation and communication technologies catalyse to development of highly automated systems in operators’ (Pilots, Air Traffic Controllers- ATCO) 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 and Next-Gen. One of their main objectives is to bring an extensive range of innovative solutions to the current aviation problems and as well as to cope with future aviation problems. These investigations have been introduced to countless technological and system innovations in operators’ working environments. 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. 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 (onboard and remote) and ATCOs, are in transition from active endogenous control to passive monitoring due to the introduction of the intensive automation. It 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. These transitions also introduce several vital changes in operators’ works and more aviation-related problems into the system. As the level of automation was increased, the human factors, situation awareness and decision-making process of the operator became more critical.

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 and create some sensors and performing test measurement, third, to investigate some unique aspects that
influence safety like misunderstanding of communication systems and last, to build operator load management systems by using the measurement. Advances in sensor and data integration technologies in the current aviation systems, allow us to collect, measure, monitor, and evaluate data prospectively with innovative devices. Such applications like microsensor, eye-tracking device, heart rate monitor, electrodermal activity (EDA) device, motion cameras and outside measuring equipment were used in the flight simulator and ATC/ATM simulation laboratory of the Department of Aeronautics, Naval Architecture and Railway Vehicles (VRHT) at Budapest University of Technology and Economics (BME). This research was done on developing a working environment to collect information on operators’ activity with different applications with the aim of increasing situational awareness and balancing total loads on the subject. Various methods and systems were tested to develop such a system. The result of this thesis suggested that in the flight simulator practice, the developed load management method serves as an excellent tool for improving the quality of pilot training. According to the test results, the load monitoring and management system balance operator total load, thereby increasing the safety of operators’ action in an abnormal/emergency situation. Due to the consequent of this development in this research:

- Monitoring operator total loads
- Managing operator actions
- Increasing the level of situation awareness
- Balancing operator loads on subject
- Better decision making and improving the quality of decision
- Increasing operator effectiveness and productivity
- Increasing safety particularly in abnormal/emergency situation

The innovation of this research is the following: (i) with rapid change in the automation, the role of operators in the transition from active controlling to passive monitoring. Therefore, (i) innovative and “out of the box” ideas are needed to deal with new situations, (ii) including information, communication and mental load to total load system, (iii) introducing a total load management systems based on the continuously monitoring, (iv) developing a methodology for measuring total load systems.

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 will be described, such as operators’ roles, working environments, human factors, and models. In the second chapter, the new operator models will be developed, such as “general load model”, “situation awareness and decision making model”, “information model”, and “subjective decision
model”. In addition to this, pragmatic failure of operators will be investigated, such as misunderstanding in aviation communication. In the third chapter, the load monitoring systems will be developed such as eye-tracking, heart rate monitor, an EDA (Electrodermal Activity) device (OBIMON) and integrated microsensors, and the measurements results will be shown. In the fourth chapter, operator load management systems for underload and overload situations will be built by using the measurements. The mathematical representations of operators’ load management systems will be given as well. Finally, the summary, major results, theses, and recommendations for the future works will be presented in Chapter 5.
Chapter 1

1 The role of operators in future aviation systems

This chapter mostly deals with the identification, evaluation, and selection for future investigation of the available literature, and at the end of each sub-sections, I tried to show how these systems can be developed and applied in future aviation.

1.1 Role of operators in aviation systems

Undoubtedly, the role of the operator in aviation will continue to be affected by automation. While technology has helped drive improvements in the aviation industry, automation has also increased significantly and is going to go on advancing at an increasing rate. In current technology, avionics systems are capable of carrying out many tasks that need to be performed by operators. According to Parasuraman, automation is a device or system that accomplishes (fully or partially) a function that was previously carried out (fully or partially) by the human operator [1]. Automation in aviation can be defined as an innovative and modernised technology to monitor and control devices or systems to reduce the need for operator intervention and activities. In aviation, most of the operator tasks rely on automation, whether s/he wishes to perform a task by automation or s/he could only hardly operate a system accurately and safely without automation (for example insufficient time). Moreover, the Level of Automation (LoA) can vary from the lowest level of fully manual performance to the highest level of full automation.

The first signs of aircraft automation were introduced on-board aircraft during the decade from 1920 to 1930, in the form of an autopilot based on a mechanical engineering concept that was designed to keep the aircraft flying straight [2]. In the 1960’s warning and alerts, systems were developed, and in the 1970s, engine fire warning systems were installed in the Boeing 707, Boeing 747, and Boeing 777 [3]. From the 1970s up to current times, there were countless innovations introduced on-board aircraft that enhanced safety: electronic autopilots, auto-throttle, flight directors, airborne weather radars, navigational instruments, inertial platforms [2]. In parallel to increasing the level of automation, a large number of aerospace companies, universities and institutes are working on advanced autonomous systems for
future air systems. Several international projects have been initiated for improving future aviation systems such as European SESAR – Single European Sky ATM Research [4], US Next-Gen – Next Generation Air Transportation System [5], Japanese CARATS – Collaborative Actions for Renovation of Air Traffic System [6], Brazilian SIRIUS – Impulsionando o Desenvolvimento do ATM Nacional [7] or autonomous unmanned aircraft, small and personal aircraft [8]; [9]. One of their main objectives is to bring an extensive range of innovative solutions to the current aviation problems and as well as to cope with future aviation problems. The new millennium had been started with developing “new visions”, like National Aeronautics and Space Administration (NASA) BluePrint [3], Vision 2020 [4], Flightpath 2050 [5], Strategic Research and Innovation Agenda [6] for description the future aeronautics and aviation. Authors of these visions have underlined, the aviation has passed through two significant `S curve` developments; such curves are known from the innovation diffusion theory [7]. The first one is the pioneering era, while the second was started by introducing the gas turbines and developing commercial aviation after World War II.

During the early days of aviation, there were five people in the cockpit: A captain (pilot in command), a first officer (co-pilot), a flight engineer, a navigator, and a radio operator. First, the “Radio Operator” was eliminated because technology had advanced to let the pilots use the radios directly up to the 1950s. Then with the advent of the “Inertial Navigation System” (INS), the “Navigator” became redundant from the 1970s. Moreover, with an increase in the level of automation, “Flight Engineers” began to disappear until the 1980s [10]. Up until now, aircraft requires only two pilots in the cockpit and only long-haul flights can have five pilots on board to take turns between flying and resting. At any given time of a flight, one pilot, typically captain, is actively flying the aircraft and performing all major controls while the other, second in command (first officer), is responsible for monitoring the instrumentation and assisting the captain. Both are highly qualified individuals and are capable of taking over the entire operation of the aircraft in any situation where one becomes incapable. The current technology motivates the numerous ongoing research to reduce the number of pilots required on-board to one, where only a single human pilot is on-board. For example, major aircraft manufacturers like Boeing, Airbus, and research centres like NASA have been working on the “Single Pilot Operation” (SPO) for about two decades. In case of assistance is needed in SPO, a robot pilot on-board (Figure 1) may serve as a first officer and/or second human pilot on the ground may be linked to the cockpit via digital data-link, video, and/or radio.
Ground operators will be able to serve in the first officer role and monitor and manage several flights at the same time. SPO concept has been an understudy in the “Flight Deck Display Research Laboratory” (FDDRL) by NASA that features one seat in the cockpit for a captain and one on the ground, occupied by an operator filling the role and responsibility of either “super dispatcher” or “first officer”, seen in Figure 1 [12]. Ground operator (super dispatcher and first officer) will be able to control and manage all of the functions in the cockpit as he were right in the cockpit. A super dispatcher can control up to twelve aircraft at once, and if there is an abnormal or emergency situation on one of the aircraft, s/he becomes the first officer dedicated to that specific flight. Besides the advantages of SPO, there is a need for finding out emerging human factors issues would be generated by situation awareness, decision-making, fatigue, stress, psycho-physiological condition, unbalanced operator loads and incapacitation. With the redundancy of the second pilot, it might be tough to monitor and manage the health of the single pilot in command with the current system. Such health monitoring systems are required to detect vital health signs of a single pilot on-board and manage his actions, respectively, particularly in an abnormal/unforeseen situation. Such measuring systems were integrated into the operator’s working environment in order to monitor the health parameter of operators and as well as manage operators’ total load systems such systems: heart rate monitor, eye-tracking systems, microsensors, electrodertmal activity device (EDA), and so on [13]; [14]; [15]. The next step for commercial flight is to the possibility of pilotless aircraft (unmanned aircraft) which are flown without a human pilot on-board and is either remote control by a human operator and fully controlled from another place (ground, another aircraft, space) or programmed and fully autonomous by on-board flight systems [16]. In both cases, ground operators in the control tower will be monitoring all the flights and will able to take over the cockpit at any sign of trouble such as malfunction of the automation system, loss of control by hackers or any abnormal situation. These are still open questions about the SPO and pilotless operation, such as what happens when an unmanned aircraft gets an accident? Who will be responsible for the crash? Who is to blame?

Figure 1: Automated Flight System, robotic cockpit (on the left) [11], NASA’s Single Pilot Operation (SPO) ground station; super dispatcher position (right) [12]
Airlines, software developers, system engineers, ATCOs or non-flying pilots? More automated systems, technologies and researches would be needed for the single-pilot operation and those without humans in the cockpit.

In the case of ATCOs, they coordinate the movement of air traffic, taking responsibility for the aircraft’s safety and ensuring that safe, efficient movement of the air traffic including the ground, terminal and en-route operations. ATCOs typically do the following: (i) keeping radio and radar contact with aircraft, (ii) monitor and direct the movement of aircraft on the ground and in the air, (iii) control all ground traffic at airport runways and taxiways, (iv) issue landing and take-off instructions to pilots, (v) transfer control of departing flights to other traffic control centres and accept control of arriving flights, (vi) providing information to aircraft about weather conditions, runway closures, and additional critical details, (vii) handling unexpected events, emergencies, and unscheduled traffic. With increasing traffic complexity and stress on conflict detection and resolution, the available time for situation awareness and decision-making might play the most crucial role in the success of the performed actions [17]; [18]. Secondly, with the aviation industry experiencing continued growth in modern times, the responsibility of operators is changing from actively operating the systems to monitoring, managing and supervising its operations, thus making ATCOs’ job more monotone. In case of an abnormal or an emergency situation, ATCOs as operators might solve the problems based on their knowledge-based behaviour. Therefore, human aspects and mental condition will have an even higher role in the future ATM, compared to the present circumstances. The human as an operator is not only an element of the system but s/he controls and manages the avionic systems. Nowadays, the operator plays a determining role in operational safety and security. Therefore, human behaviours, working ability, the human-machine interface, interaction, and working environment must be studied in detail. Even more, by increasing the level of system automation, the role of operators is changing from their active control to passive monitoring. The operator roles, therefore, must be re-evaluated, the human-machine interface and working environment should be redesigned. In the future system, the operator support systems must be widely developed and applied. These systems will contain (i) sophisticated info-communication systems, (ii) monitoring the operator total loads and, (iii) supporting the situation awareness and decision-making processes. These future operator supporting systems can be used in the car drivers’ environment as well [19]; [20].
The revolutionary new technologies have a dramatic influence on the development of the car drivers' support systems as a set of sub-systems and system elements. At the same time, the replacement of the existing vehicle driver environment by future solutions may cause disharmony in drivers, developers and researchers' expectations [19]; [23]; [24]. On the one hand, drivers would like to have an exciting and pleasant interface (Figure 2, right). On the other hand, the future car developers may think about the highly automated and even autonomous vehicle that needs minimised instrumentations that also might be better to name only as entertainment. The vision of the researchers is to develop more and more special solutions, devices for increasing the situational awareness and decision quality of drivers. The car systems, therefore, need to be adjusted based on changes in the physical characteristics of drivers. In a current automobile technology, developed biometric sensors can be placed in a position where can easily detect the driver's vital health parameters and behaviours [23]. All the necessary information can be stored in order to control drivers when it is necessary, such as being under an abnormal/emergency situation. The future operator supporting systems will contain the following: (i) sophisticated info-communication systems which provide information about the operational condition of the vehicle, (ii) monitoring and managing the total operator loads which contain three branches:

- **Situation Awareness**: (i) physiological measurement, (ii) cognitive measurement, (iii) proximity detection, and (iv) characteristics of perception and sensitivity
- **Decision-Making and Response Selection**: (i) stopping and passing decisions, (ii) dilemma measurement, (iii) mental workload, and (iv) driving psychology analysis
- **Operation and Execution**: (i) analysing emergency operating behaviour, (ii) analysing braking behaviour, (iii) analysing follow-up behaviour, and (iv) physical workload and lastly (v) simultaneously tweaking the necessary vehicle units to support response time of driver (adjusting suspensions, torque vectoring, etc.).
The technology developments initiate the transition from these human – operator centric models to human load models in which the role of human personal behaviours, knowledge, and practice of operators is significantly increasing.

1.2 Changes in operators’ role by developing future aviation systems

Operators are still central elements of the system defining the safety level of air transport, but in the near future, they will be transformed to be a passive element [25]; [26]; [27]. In the new state, operators will be monitoring the operation of automatic systems and will have an active role only in abnormal/emergency situations. In other words, by developing and introducing the highly automated systems, operators would not be involved in active control but would be in a passive role of monitoring, as can be said to supervise the aircraft and air traffic [15]. Therefore, the operator models, and load monitoring and management become the level of the most critical tasks. These new avionic systems require more thought, new sills, high-quality decisions and as much as fast actions. The work quality of passive operators depends on their loads, namely, work, task, information, and mental load. Notably, the information and mental load as physical - psycho-physiological conditions play a much more significant role in future systems. On the one hand, it seems that aviation systems are or going to be highly automated that little effort is necessary to control them as long as the automation system is properly functioning. On the other hand, automation systems bring disadvantages to the aviation environment such as increasing mental and information load of operators or lowering handling skills, particularly when avionic systems fail or under being an abnormal situation. According to Karsvall [28], in highly automated systems, the human operator needs to be involved in technological advancements to be able to operate machines and equipment during unforeseen situations [29]; [30]. In a NASA study of human factors in advanced automated aircraft, the pilots noticed when the automation failed and found that the automation increased the workload during flight times with an already high workload and decreased during times of low workload [31]. According to a Boeing statistical summary report, with the rapid expansion in automation, the accident rate worldwide has fallen dramatically; however, this rate has stagnated since the 1980s [32]. Moreover, operator load systems play a determining role in the so-called subjective situation awareness and decision-making of operators. Operators make an appropriate decision based on the information which is obtained from the system and other operators. With advanced technology and automation, operators receive a large amount of information in the modern cockpit in order to better control their aircraft operation. However, sometimes too much and partly not harmonised
information from different sources can confuse operators, and they became incapable of dealing with too much information. As a result, operator loads get higher, mainly informational and mental loads. There have been several aviation disasters in the last 15 years that can be attributed to automation-induced errors such as Germanwings Flight 9525 (2015), B777-200 San Francisco (2013), A340-300 Paris CDG (2012), A320 Tel Aviv (2012). Before automation became so dominant, such the aircraft accidents which related to mental load were not so frequent. Mental load (physical and psycho-physiological condition) depends on human behaviours, skills, knowledge and practice. Other disadvantages of automation are certainly the risk that decisions and actions will not be driven by human-centred principles but by machine centre. These changes in the level of automation make automation system insufficient in coping with abnormal events. In 1996, The European Organization for the Safety of Air Navigation (EUROCONTROL) described twenty-three cluster tasks which are divided into four sub-tasks: (i) core tasks, (ii) cognitive tasks, (iii) direct support tasks, and (iv) indirect support tasks. In addition to this, one hundred-seven sub-task was identified. The core tasks of ATCOs are listed as: (i) maintain situation awareness, (ii) make decisions for control actions, (iii) Provide pilots with all relevant information, (iv) provide separation, (v) provide A/C in abnormal situation, and (vi) provide tactical air traffic control management [33]. According to this identification, the major task of ATCO was to provide separation management (tactical command of the air traffic without conflicts) while supporting pilots with relevant information and as well as assist them in abnormal situation/emergencies. To deal with these tasks, ATCOs must implement their tacit knowledge and skill in “situation awareness”, “decision-making”, and “action” processes. As mentioned in section 1.1, ATCOs coordinate the movement of aircraft to maintain safe distances between them. They provide for the safe and orderly flow of air traffic in the assigned airspace or airport. With increasing the levels of technology, ATCOs are not going to be dealing with all the previously defined cluster tasks. Some of these tasks are going to shift to pilots or rely on automation to do that for ATCOs. Even though if the future role of ATCOs becomes passive monitoring, they are still responsible assistance in abnormal circumstances. Figure 3 demonstrates the process model of ATCOs core task in future aviation systems.
These changes will define new requirements regarding ATCOs’ individual skills, knowledge, and competence, which might require new systems and interfaces to support their modified roles and responsibilities. With the developments of NASA’s Blueprint Project, Flightpath 2050, SRIA (Strategic Research and Innovation Agenda) and ACERE (Advisory Council for Aeronautics Research in Europe), the role of ATCOs in future aviation systems are identified in terms of capacity, safety, security and efficiency (Figure 4). These goals are expected to be reached by the application of the latest results of sciences and technologies, and the implementation of a series of new principles such as performance and trajectory-based movement, or airborne net-centric services (Figure 4). All these improvements led to airspace redesign.
Nowadays, several international projects are launched, aimed at modernising the coming air traffic management to cope with the present problems, including, e.g. airspace capacity, efficiency, air traffic complexity and environment [35]; [36]; [37]; [38]. The SESAR project develops a new method for sector design and airspace configuration. One of the large projects in SESAR deals with the investigation of ATCOs workload management. And one of the possible management when sectors, the airspace is usually divided into smaller regions referred to as sectors, are dynamically changed with an aim of making the configuration of the airspace less complex in terms of both its uncontrolled/controlled airspace classification and its international boundaries. This is the so-called “Dynamic Airspace Configuration”. Introducing dynamic airspace configuration will significantly decrease total operator load, and the complexity of the overall route structure and airspace system. A special workshop organized by Budapest University of Technology and Economics for validation of the exercise performed in the scope of the SESAR program in France. During the workshop, a series of questionnaires were used for the evaluation of the opinions of experts. The current researcher took part in this project in the assessment of results. The main goals of the project was: (i)
balance the sector workload for ensuring safety, (ii) decrease operator total loads, (iii) better use of availability of airspace, (iv) offer the maximum capacity to the incoming air traffic, (iv) best meet traffic demand at peak times operate with less staff, (vi) reduction in fuel burn and emission, and (vii) minimising all costs.

As seen in Figure 5, depend on the air traffic complexity, the total airspace can be divided dynamically into small “sectors”. The complexity of the traffic has a direct influence on a total load of operators. According to the results, the dynamic sectorization and airspace configuration may eliminate the task overload and reduce the actual load by 30-40 per cent [39]. The large size international projects, such as SESAR and Next-Gen, plan to shift aircraft separation task from the ground-based air traffic control to the airborne self-separation, as well as the “situation awareness” and “conflict avoidance” to the aircraft

Figure 6). These two aspects introduce a paradigm change in the ATCOs’ roles [34]. Next-Gen envisions [40] the five types of personal roles of the navigation service provider: (i) capacity managers in collaboration with airspace users and flight operators, (ii) flow contingency providers in cooperation with flight operators, (iii) trajectory managers in a collaboration with flight operators, (iv) separation managers (maybe flight crew depending on the airspace and the operation), and (v) automated dissemination to operators and flight crews, flight operation centres, third-party service providers.
All the developing future ATM systems have a considerable influence [41]; [42] on the operators’ roles and responsibilities. Consequently, several proposals have been initiated for modernising air traffic control to meet the demands for enhanced capacity, efficiency, and safety by several institutes and companies such as “Radio Technical Commission for Aeronautics” (RTCA) [43], “Federal Aviation Administration” (FAA) [44], and “EUROCONTROL” [45]. All these proposals have been introduced more freedom for the operators to choose their heading, altitude, speed in real-time and primary responsibility for maintaining separation from other aircraft in the immediate airspace operations. There are significant changes partially delegating some roles and responsibilities from the ground (ATCO) to on-board (pilot) and intensive automation [46]. Some of the present tasks shift from the ground to on-board (pilots) and diversify automation. For example, “Free Flight (FF)” concept as proposed by the RTCA and “Distributed Air/Ground Traffic Management (DAG-TM)” and recommended by NASA [47]. Free Flight and DAG-TM innovative concepts describe a radical change in air traffic control procedures in which the task of traffic separation has been moved from ATCO to pilot [48]. Principally, the automation will not take over the whole responsibility, trajectory management; however, it expands the ATCOs functional envelope. Nevertheless, the free flight concept shifts the air traffic management system from a centrally controlled system to a distributed system.
Free Flight concept, therefore, is a revolutionary change of the air transport system [49]. The most significant challenges of free flight are: (i) maintaining the safe separation between aircraft, (ii) potential for more efficient routes, (iii) reduced flight time, and increased airspace capacity, (iv) fuel efficiency, and (v) less dependence on air traffic control [50]; [51]. The workload of air traffic controllers would be reduced considerably by introducing these innovative concepts as well.

![Figure 7: Hungarian Free Route Airspace with border points (HungaroControl) (left) [52], and concept of dynamic routing (right, Source: Own Edition [50])]()

Figure 7 shows the concept of the dynamically designed route of an arriving aircraft from WP01 to WP14. The black path is a published transition route, the red is a shortcut given by the ATC in low traffic density, and the green line is a dynamically designed route considering noise load, aircraft energy state, etc. With the introduction of the highly dynamic approach and landing procedures, aircraft will be able to follow better trajectories, which will improve the air traffic situation by decreasing flight durations, fuel consumption, congestion and noise load [50]; [53]; [54].

1.3 Operators’ working environment

Air traffic control is a real-time safety, critical decision-making process that is highly dynamic. It is well-known that ATCOs job requires a stochastic working environment with a high level of responsibility concerning risking lives and as well as the high economic cost of aeronautical activities. ATCOs work with their colleagues at air traffic control towers where they rely on radar and visual observation to control all the movements. In today’s aviation practice, an ATCO monitors and directs many aircraft flying through its designated airspace sector. Air traffic controllers coordinate the flow of air traffic, taking responsibility for the aircraft’s safety; thereby, ensuring safe, and efficient movement of the air traffic including the ground, terminal
and en-route operations. The “Air Traffic Management System”, as it is used today, is centrally controlled. The workstation of ATCOs has changed a lot since the 1910s. Today the modern workstation is quite simple, computerised, and it integrates several subsystems into one working environment [55]. The load monitoring and management of controllers, primarily mental and information, initiate new requirements for information processing. In designing the working environment of ATCOs, it is necessary to take into consideration not only physical factors like the positioning of radar screens, lighting, auxiliary and visual displays but also subjective factors such as skill, ability, experience, loads, anxiety, and stress. Further standardisation of the panel layout is required. It is, therefore, in this research, total load (work, task, information communication, and mental load) monitoring systems were integrated and tested in the operators’ working environment. These integrated systems will help ATCOs to keep their tasks at an optimal level which has a direct connection to excellent performance and safety. For example, in the developed load monitoring system, the total loads of ATCOs will be continuously measured by the integrated devices in their working environment, and the changes of each load level will be separately demonstrated on the operators’ and as well as for their supervisors’ displays. In case of an unbalanced operator load, the supervisors and/or the avionic system automatically will be able to change the arrangement of working teams, tasks and structures such as decrease the number of aircraft under his control, responsible airspace or basically will bring some suggestions to the operators. This situation will balance total operator loads and improving the comfort and well-being of operators in their working environment. Reduction of active control might lead ATCOs less to do with telephoning, listening and conveying information; therefore, greater emphasis should be placed on the development of their attention, particularly in abnormal/emergency situations.

Figure 8: The working environments of ATCOs (left) and supervisors (right) [4]

ATCOs are working in a large and very sophisticated environment supported by different systems:
• Physical systems, technical, and technological elements – chairs, tables, computers, displays, etc.,
• Information systems are providing all the available information – aircraft performances, flight information system, weather information system, the information provided by other systems as surveillance, etc.,
• Communication systems – between the ATCOs, ATCOs, and pilots, communication between the service providers, etc.,
• Monitoring, detecting, and decision support systems, namely surveillance, conflict detection, conflict resolution – that containing the technical equipment (as radars, sensors), the principle of measurement analyses, i.e. situation awareness and decision support and software,
• Load management – based on monitoring the ATCOs loads,
• Unique extra supporting systems – like safety and security risks evaluation and mitigation,
• Rules, and operational manuals are synthesising the supporting system into the net-centric overall system.

The future ATM system that is being developed by several mega projects (SESAR, Next-Gen) under rethinking, redesigning the existing system by use of latest results of sciences and technologies ([4]; [40]; [47]). All the supporting systems will be improved, and a lot of new principles, solutions, tools will be developed (Figure 8) by innovative technologies. Some technology solutions were planned to develop and deploy by NASA’ Blueprint Project such as automated airspace, high flow airports, and digital atmosphere [47]. The new developments will generate systematic changes in future ATM as SESAR evaluates it. The future work and working environment of ATCOs might be characterized by following four major aspects: (i) ATCOs will play role of passive operator in highly automated system – instead of active separation control management, (ii) ATCOs will have a “greater” working environment; namely, they will have several displays or large screens, several windows working parallel on their computers, etc., (iii) they will be working on-line in an “off-line” environment, i.e. in remote tower environment equipped with large synthetic vision screens, etc., (iv) they will have too much information that may confuse them. The total load of ATCOs is subject to wide variation and depends on such factors as the number of aircraft supervised, the complexity of air traffic routes, individual aircraft speed and relative aircraft movement comprising fast and slow aircraft, arrivals, departures, and en-route traffic. Furthermore, air traffic controllers should be capable of spreading their attention over several tasks simultaneously. Concerning the working environment of pilots, aircraft cockpits are designed in such a way that pilots can provide excellent handling characteristics not only under normal conditions but also under critical conditions such as peak loads. Past flight deck design practices have been highly
successful in producing safe and efficient aircraft. Technology advances have provided improvements in pilots’ working environment and will continue to do so in the future. The level of automation has been changed the way pilots control aircraft and as well as their needs in the working environment, because of these changes, flight deck design needs to be reconsidered. The position and operation of controls and flight instruments are crucial for operators. Pilots have to carry out their tasks based on the information given on instrumental panels, and receiving from ATCOs and other pilots. Advances in sensor and data integration technologies in aviation systems make more information available than ever before. On the other hand, highly automated systems have increased the monitoring tasks of pilots instead of reducing control tasks. This phenomenon will also cause pilots to lose their “situation awareness” during flight operations. All controls in a cockpit should be within easy reach of the crew, and all instruments should be easy to read and understand by operators. The performance of the overall pilots and flight deck system depends on understanding the total system. This situation will permit pilots to acquire information without interference and allow them to operate all the controls efficiently for effective and safe operation.

Figure 9: Flight deck of a Douglas DC-7 (left) [56] and Boeing 787-9 (right) [57]

A comparison example of cockpit designs in the earlier days of aviation and the modern cockpit environment is shown in Figure 9. As seen in this figure, the cockpit design has been changed significantly with increasing display area and a smaller number of individual displays. In the earlier days of aviation, analogue instruments were used for information presentation since the 1960s [58]. With the introduction of new avionics systems and equipment, in the early 1970s Multi-Functional Displays (MFD) appeared in the cockpit to display information to the operators in numerous configurable ways while a gauge can only display a limited amount of data. With the advent of microprocessors, microelectronics, and Liquid Crystal Display (LCD) technology in the 1980s, the first MFDs based on LCDs with their computer within the display appeared in aircraft cockpit [59]. In the early days of aviation, researchers and aircraft designers introduced as much as more gauges onto aircraft to be able to provide reasonable information to pilots for the proper and safe performance of a flight. In cockpits designed earlier gauges
could only display a limited amount of data. However, after rapid changes in the level of automation, cockpits are designed to decrease the number of small instruments. With continuous evolution of the flight decks, including aircraft capabilities, sensor systems, and pilots are supported by huge amounts of available data and relevant information. In the current modern cockpit environment, the role of pilots became rather an information manager than an operator. The huge amount of available information confuses pilots during operation, particularly while decision-making time in abnormal/emergency situations. While the introduction of new technology brings significant improvements and may solve some problems, it often introduces others. For example, with the introduction of advanced automation, cockpits became very automated. While the responsibility of the pilot to fly safely remain unchanged, several new skills are required to control aircraft. The future working environment of pilots (cockpit and future ground control tower of pilots) needs to be designed by taking into account various psychological and human factors. According to Endsley [60], pilots will face with the followings in the next-generation cockpits: (i) increased vigilance & monitoring, out-of-the-loop performance problems, (ii) more cognitive load, (iii) loss of manual skills, and (iv) mode errors. In order to cope with these situations, the developed systems can be used in the working environment of pilots, thereby increasing “situation awareness” and the quality of decisions. A number of research studies have sought to investigate the relationship between operator workload and operational errors. Operational errors have been found by M. Endsley [61] to occur under both high and low workload conditions, with more errors occurring under low and moderate levels of the workload than under high levels of workload. However, in the continually changing aviation systems, it is necessary to define what degree of total load operators receive from the current system. Automation should increase overall performance and reduce the chance of error by lowering task demands on operators. According to [62], operators only monitor what an autonomous system is doing, but if an operator does not know well why and how it is doing it, and what it will do next, the autonomous system will contribute high loads to operators. Operators need viable constructs, principles and aviation systems to promote a better understanding of automation and controlling their load in complex circumstances. This thesis work comprises the evaluation, monitoring, and management of total load systems of operators, considering their current needs. In that context, the load monitoring devices were created and performed measurements in operator working environment.

1.4 Human factors in aviation

The human factor is the study of the relationship between (i) humans (body and mind), (ii) human beings and systems, human beings and technology, and (iv) human beings and working environment by focusing on improving efficiency, productivity, safety and security to
minimise human errors. Within the context of aviation, studies include the interactions and effects among operators, their working environments, equipment, and systems. The field of human factors dates back to World War II in the area of aviation, and its importance has grown increasingly up until today. Human factors in aviation deal with operator performance, behaviour, abilities, limitation, stress, anxiety, fatigue, cognitive loads (work, task, information, communication and mental load) and culture. It is necessary to manage human aviation factors and their effects on flight crews and among others, in order to reduce operator mistakes. Human factor awareness in aviation is critical to optimise the fit between operators and the systems in which they work in order to improve safety, security, and performance. Aircraft accidents and incidents almost always result from a serious of events, each of which is a combination or interaction of several factors. An example might be when an aircraft accident was made to avionic causes, severe weather and unbalanced operator load. As in most aircraft accidents involving humans and systems, there were a number of human errors that caused severe air disasters. According to Boeing [63] today, approximately eighty per cent of aircraft accidents were caused by operator error, and the other twenty per cent is mainly due to mechanical failure and weather-related flying conditions. Back in the early days of aviation, it was the reverse, close to eighty per cent of aircraft accidents were caused by the machine and the other twenty per cent were caused by operator error (Figure 10).

Figure 10: Causes of Accidents (data taken from [63])

Figure 10 shows that operator interactions get more critical by years. Today, this means that over time situation awareness, decision-making process and operators’ total loads become the main driver. As seen in Figure 11, there is a change in focus and priorities of human factors in aviation over time: human workload in aviation became a priority between the 1940s and 1970s. From the 1970s through the 1990s, situation awareness received the highest focus. With continually changing aviation technology, organizational safety and as well as supervision of human mistakes were the main driver from the 1990s through the 2010s. From
the 2010s to the present, mental load and information load, and operator decision-making process have been a driver.

![Chart of Human Factor Priorities](chart.png)

Figure 11: Human Factor Priorities evolved over time (the data partly taken from [64] and recreated with more details by the current researcher [27])

Petersen [65] is among many who believes that human error is the fundamental cause behind all accidents. Human error is now the primary risk to flight safety (Civil Aviation Authority - CAA [66]). Accident investigations have been shown that human factors could be divided into three groups depending on their origins.

- Technical factors: Disharmony in the human-machine interface: most known cases from this group are called “PIDs” (Pilot Induced Oscillations) and such types of human factors are taken into account in aircraft development and design processes. Some of these factors, like limitations of the control stick forces, are included even into the airworthiness requirements,

- Ergonomic factors: It has been investigated for over 60 years. These factors have been used in the cockpit design such as ergonomic information display, guidance control, out of cockpit visibility, and instrument panel. The psychophysiological behaviours of the operator play determining roles in the operation of the system,

- Subjective factors: Wrong decision-making due to lack of knowledge and practice of operators such as un-predictable and non-uniform operator behaviour.

Operator errors during the decision-making process might be due to such factors as under/overload, stress, fatigue, available time, lack of tacit knowledge, etc. while during performance action might by lack of adequate procedures, poor flight deck design. According to James Reason [67], human errors can be divided into two categories: the person approach
(errors of individuals) and the system approach (working condition of humans). James Reason proposed the model of „Swiss Cheese” to explain the occurrence of system failure [63]; [68]. According to this model, accidents and incidents are caused by a set of errors in complex circumstances. Each layer has several holes that represent individual weaknesses in individual parts of the system – hence the similarity is more like slices of randomly-holed Swiss cheese. These holes are arranged vertically and parallel to each other with gaps in-between each slice, and continuously opening, closing, and changing their location depends on the current situation in complex systems. When by chance, all holes are aligned, this can cause unfortunate outcomes such as accident and incident.

![Swiss Cheese Model](image)

Figure 12: The Swiss cheese model (SCM) of pilot error causation [18]

Figure 12 shows the “Swiss Cheese Model” of how an accident trajectory may penetrate an aircraft accident. As seen in Figure 12 that the aircraft accident might be occurred by having multiple human errors or system failures in each level in the system line up that influencing each other (passes through holes in all of the defences) such as loss of situation awareness, distractions, lack of experience and inadequate training.

In order to identify and classify the actual and latent causes in a systematic method, “Human Factors Analysis and Classification System” (HFACS) was generated. HFACS is a well-known framework [69] for identifying, analyzing and classifying the underlying human factors associated with accidents and incidents in aviation that is based on a chain of-events theory of accident causation. HFACS framework was derived from James Reason’s (1990) accident model and initially developed and tested by Shappell and Wiegmann [65] in the United States. Since its development, the classification system has been used in a variety of military and civilian transport and occupational settings. The HFACS classification system describes four levels of failure [70]: i) Unsafe Acts (errors and violations), ii) Preconditions for Unsafe Acts (substandard conditions of operators and substandard practices of operators), iii) Unsafe Supervision (Inadequate supervision, planned inappropriate operations, failed to correct
problem and supervisory violations), and iv) Organizational Influences (resource management, organizational climate, and organizational process).

Some of the other most prominent examples of human factors in aviation are language and culture, which lead to poor decisions and errors often result. In comparison to many other threats to aviation safety and security, pragmatic failure in aviation communication and cultural misunderstanding can be more challenging to avoid [71]. In general, people convey information and messages to others through verbal (face-to-face, telephone, radio, television or other media), non-verbal (gestures, body language) and writing communication (e-mails, books, magazines, social media). The transmission of the message from speaker to hearer can be affected by a huge number of factors, including cultural situations, social customs, emotions, etc. In face-to-face communication, the spoken content can be interpreted by processing visual cues, such as mimicry, deliberate signals (e.g. eye signs), facial expressions, gestures of the face, hand, and body. In aviation communication, however, pilot and air traffic controllers are neither in face-to-face contact nor have a video speech interface between them while communicating with each other; therefore, they need to communicate solely through speech. Their communications are conducted entirely through radio messages using a specialised language designed to make communication as accurate and efficient as possible (International Civil Aviation Organization-ICAO [72], and FAA [73]). Therefore, their sense of listening and speaking play a very important role. According to Sauer [74] gesture is, at the same time, a noun and a verb. Therefore, even if operators use the same language and want to convey the same messages, the interpretation of the messages sometimes can be different depending on the hearer due to the same factors such as incorrect communication, cultural norms, social relations, etc. Sometimes pilots cannot express the desired meaning one to another. In other words, the message of the operators (pilots, ATCOs) can be misinterpreted over radio communication. Misunderstanding can occur at any stage of the communication process between the pilots and traffic controllers. Misunderstanding and communication difficulties have been considered as a major factor in aircraft incidents and accidents. For example, the most well-known and widely discussed accident in aviation history is the Tenerife air disaster which took place on March 27, 1977, [75] when two Boeing 747 airliners collided at Tenerife North Airport in Spain, which resulted in 583 fatalities (61 survived) - making it the deadliest air disaster in aviation history. The incident was due in part to difficult communication and to a misunderstanding between the Dutch-speaking pilot, and the Spanish air traffic controller. In this accident, the pilot of the KLM aircraft reported to the ATCO “we are now at take-off” and received the reply “OK. Stand by for take-off” which was partly masked by noise. In this event, the pilot meant to say “we are now on the take-off roll” or “we are now taking-off”; however, the controller mistook his statement to mean the aircraft was at the take-off point, and the pilot was ready for take-off, awaiting further instruction [76]. Actually, the KLM aircraft was taking off without clearance from the ATCO and was about to
collide with the Pan American aircraft, which was already on the runway and taxiing toward the KLM aircraft. The Tenerife accident was caused by misunderstandings between both non-native English speakers of the KLM pilots and the ATCO. Another example is the misunderstanding that happened in 2006, during the time Air China 981 was taxiing to the gate after a 12 hours’ flight from the Beijing Capital Airport in China. Due to the different cultural norms and poor language skills, Asian pilots have difficulty to speak and understand the language both in communication with air traffic controllers and with other pilots (particularly for elderly pilots). The final radio transmission of the Air China 981 accident had shown that the Air China 981 pilot could not understand English properly when he was replying to the air traffic controller [77]. In order to effectively communicate with operators (pilots and ATCOs) between both native and non-native speakers of English, the use of aviation English is needed to avoid any confusion or misunderstanding. According to a survey of the U.S. NASA Aviation Safety Reporting System (ASRS), 80 per cent of aviation incidents or accidents can be traced to incorrect communication (Table 1) [78]; [79].

<table>
<thead>
<tr>
<th>Factor</th>
<th>Per centage of Reports</th>
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<tbody>
<tr>
<td>Incorrect communication</td>
<td>80%</td>
</tr>
<tr>
<td>Absence of Communication</td>
<td>33%</td>
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<tr>
<td>Correct but late communication</td>
<td>12%</td>
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</table>

Table 1: Communication Factors in NASA ASRS Reports [80]

The International Civil Aviation Organization (ICAO) instated English as the official language of aviation in 1951 to avoid confusion, ambiguities and misunderstanding between the cockpit and tower communication, thereby increasing the safety of flight. ICAO aimed to make communication much easier in a large worldwide air transportation system. It is well-known that the native English speaker of operators makes fewer communication mistakes compared to non-native English speaker of operators. However, English is not the native language of most pilots and air traffic controllers. Even with a common language, communication can still be challenging due to heavy foreign accents, poor language skills, speech rate, different pronunciations and using slang, etc. The ICAO has introduced language proficiency requirements for flight crew members and air traffic controllers with a rating scale from “pre-elementary” (Level 1) through “expert” (Level 6), mentioned in the ICAO Amendment 164 to Annex 1. Pilots and air traffic controllers must be qualified and certified at least at an “operational level” (Level 4) of English proficiency in order to carry out their duties effectively with regard to international aviation. According to the ICAO language proficiency standard,
pilots and air traffic controllers should have the ability to speak and understand the language used for radiotelephony communications specified in the language proficiency requirements in Appendix 1. [72]. The objective of the International Standard for Language Proficiency Requirements is to improve the level of language proficiency globally and aeronautical radiotelephony communication, thereby reducing the frequency of communication errors.

On the other hand, pragmatics plays a critical role in aviation communication. Pragmatics is a subfield of linguistics that studies the ways that context affects meaning due to several factors such as cultures, values, norms, religion, social background, etc. All these factors can vary from person to person, and these differences can also assign inaccurate meanings to words. An example of pragmatic failure is given in aviation. Eastern Airlines L-1011 jumbo jet crashed at night in the Everglades near Miami in December 1972. The aircraft, Flight 401, had been assigned to circle at 2,000 feet while the crew tried to fix a suspected nose-gear malfunction. Apparently, none of the distracted crew members noticed when the automatic "altitude hold" device disconnected and the plane began a nose-dive. A traffic controller following the aircraft on radar did notice. When the scope showed the jumbo jet down to 900 feet, he radioed:

ATCO: "Eastern, ah, 401, how are things coming along out there?"
Pilot: "O.K., We'd like to turn around and come back in."

The crash followed half a minute later; 99 (94 passengers and 5 crew members) of the 176 people aboard suffered fatal injuries (Aircraft Accident Report [81]). In the accident of the Eastern Airlines L-1011 at the Miami airport, the aircraft had two technical issues. The first one was the aircraft was losing its altitude and the other one an in-operative nose gear light. The air traffic controller radioed the pilot when he was aware of the elevation problem; however, the ATCO did not know about the issue of the nose gear light at the time. When the ATCO asked the pilot in command "Eastern, ah, 401, how are things coming along out there?" which the pilot assumed to mean that the ATCO was talking about the issue of the noise gear light and replied to ATCO "O.K., We'd like to turn around and come back in." Both of them were referring to different technical issues while the aircraft was about to crash into the everglades.

Let's have a close look of the ATCO's message: "Eastern, ah, 401, how are things coming along out there?". In this message, "how are things coming" is not entirely clear because it is not well known which the ATCO means "things". Pilots can interpret this information with a different meaning. What does "things" mean in this message? As soon as the ATCO says "things", the meaning must be analysed through pragmatics, because only from the context is it possible to know what things are referred to.

"How are things coming along" is quite a low register (colloquial). In a low register, more of the meaning is usually conveyed through pragmatics. Low register communication, as one
would talk with a good friend, is to be avoided in aviation communication, because words are in general not precise. In this situation, the pilot inferred (filled in) the meaning. Therefore, this example relates to pragmatics. Pragmatic failure refers to the uncorrected misunderstanding of pragmatic meaning. In order to avoid pragmatic failures, the ATCO must be as precise as possible in his message. Moreover, meaning should be conveyed as much as possible at a semantic level. Instead of saying "Eastern, ah, 401, how are things coming along out there?", the ATCO could have said "Eastern, ah, 401, you dropped to 900m. Please explain." A questionnaire was conducted in order to investigate the reasons for communication errors of operators (pilots, ATCOs) related to several factors such as cultural norms, regional accents, and poor language skills. This survey consisted of four groups aimed to find a way to avoid pragmatic failure in aviation communication. In passing, some results of questionnaires will be demonstrated in Chapter 2.4.

1.5 Operator models

The operator model can be defined by three different approaches: (i) situation awareness and decision-making model, (ii) load model, and (iii) information model. In aviation, a lack of situation awareness is often attributed as the cause of negative safety outcomes, such as incidents and accidents. For decades, loss of situation awareness (SA) has been cited as the cause of accidents attributable to human error in operators [82]; [83]. Benton J. Underwood can give one of the earliest references to the situation awareness concept in his classic book of "Psychological Research" [84]. However, situation awareness did not receive enough attention until its use in military communities necessitated an operational definition. The first sign of the development of the situation awareness construct by Endsley [85], and other researchers such as [86]; [87]. Now, many scientific descriptions can be found in this field [88]; [89]; [90], and [85]. Endsley defined situation awareness as “perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future” [60]. Endsley [85] suggested a component model where a simulation-based tool was developed, known as the Situation Awareness Global Assessment Technique (SAGAT). This tool was used to measure the situation awareness of pilots [91]. Taylor [89] proposed measuring situation awareness using a somewhat similar method known as the Situation Awareness Rating Technique (SART). Figure 13 provides a model of the role of “situation awareness” in the decision process adapted from Endsley [82]. As seen in Figure 13, situation awareness is affected by environmental factors, individual characteristics, workload, and pre-conceptions and objectives. In this model, situation awareness contains three different levels: (i) Level 1 is the critical factors in the environments, (ii) Level 2 is, understanding what those factors mean, and (iii) Level 3 is, understanding of what will happen with the system in the near future. This model was one of the well-used
models up to date and clearly described situation awareness and its connections well. However, situation awareness factors and the type of problems are continuously changing in parallel to the rapid technological changes. For example, as stated earlier, with the current aviation systems, automation has been altered the role of operators from active control to passive monitoring. Due to this change, the workload of operators tends to balance with some of task rely on automation; however, on the other hand, operators have been started to receive high information and mental load. The Endsley “Situation Awareness Model” was improved upon, by the current researcher, by including the “Present Situation”, total load systems and as well as extending the “Task/System Factors” and “Individual Factors”. This situation awareness model allows researchers to evaluate and determine the most appropriate actions according to the stipulated objectives. The detail explanation about the newly developed situation awareness model will be shown in Chapter 2.

Figure 13: Role of situation awareness in the decision process presented by Endsley [60]

The NASA Task Load Index (NASA-TLX) is a multi-dimensional rating procedure that provides an overall workload score based on a weighted average of ratings on six subscales: Mental Demands, Physical Demands, Temporal Demands, Own Performance, Effort, and Frustration [92]. In the dynamic flight environment, the decision-making process of operators is highly
dependent on situation awareness. Operators use subjective decisions [20]; namely, they apply subjective situation awareness, situation analysis and decision process in aircraft controls. Firstly, the level and type of problem need to be defined and after they must choose the best solution from a set of available resources (methods or technologies). Resources can be divided into two categories: (i) “active resources” which can be related to aviation systems such as finance, information, materials, and (ii) “passive resources” which can be connected to operators such as physical, psycho-physiological behaviours, and possibilities of subjects. Subjects (system operators) can develop their active resources or competences with theoretical studies and practical lessons [93]; [94]. However, the ability to choose and use the right resources in optimal time is highly dependent on (i) information support, (ii) tacit knowledge, (iii) way of thinking, and (iv) skills of the subject. Such decisions are the results of the subjective analysis. Secondly, operators make a decision on control after evaluation of the flight situation awareness. The quality of the decision also depends on the available information and psycho-physiological condition of the operator, which can be improved by the developed systems. The aircraft conventional control systems including “operators in the loop” are called active endogenous systems, because the operators react actively to real situations evaluated by them and their solutions origin from their minds, from the nervous system. Over the past years, there has been much talk about operator workload. The operator workload plays an essential role in the flight environment, and most of the operator errors and performance decrements can result from causes beyond a loss of situation awareness and overload. The workload can be defined in a variety of ways. The various definitions and theories of workload agree on the statement that workload is an interaction between the operator and their tasks. Thus, elements of the task and characteristics of the operator are contributors to workload. According to Huey and Wickens [88], the workload of operators contributes in a complex circumstance (cockpit and ATCOs workstation) from four factors: (i) performance criteria, (ii) task structure, (iii) human system interface, and (iv) individual factors. According to his statement, operators are under pressure because they are expected to perform high with minimum errors. Multi-tasking, the complexity of task and information, and time pressure can be addressed such factors that lead to increase workload. Individual factors, such as tacit knowledge, stress level, and experience of operators, have the potential to overload. According to Huey and Wickens [88], all the load systems were included in the calculation of workload. Sarno and Wickens [95] state that the main contributor to operator workload is task load. Moreover, Watson et al. [96] have a similar statement that task difficulty has a significant influence on operator workload. Numerous researchers have reported that mental workload is a crucial factor in determining operator performance in the working environment. Most of the previous researchers were tried to calculate workload in connection with operators’ tasks and mental conditions. However, due to rapid technological changes in aviation technology, operators receive too much and partly not harmonised information from the different sources
than the early days of aviation. These changes have introduced a new type of operator load system, namely information load. In this thesis, the total load system will be described into five (four plus one) groups: (i) workload, (ii) task load, (iii) information, (iv) mental load and as well as (v) communication load. It is, therefore, necessary for an accepted means of measuring operator total load. To do so, in this research, such different measuring methods were devised and tried to measure operator total load systems by the integrated devices such as eye-tracking device, heart rate monitor, electrodermal activity device, etc. The design and operation of the modern aircraft system must take into consideration this operator load monitoring and management seriously. In order to control aircraft safely, operators must not only know how to operate the aircraft and follow the pressures, rules and regulations, but they must also deal with continuous situational awareness and decision-making process. However, to keep a high level of situation awareness in-flight dynamic environment is one of the most challenging tasks for operators. According to a study of Endsley [82], eight per cent of them involving human error could be linked to issues with situational awareness. In an abnormal or emergency situation, flight safety does not only depend on available information, but the whole picture including space, time, tacit knowledge, experience and loads of operator on the emergency situation plays the central role. Operator training can also be a useful mechanism for improving situational awareness abilities. In order to understand how to monitor and measure a total load of an operator, it is crucial to have a clear understanding of how operators acquire and analyse information for “decision-making” and “performance action”. Various studies in the literature try to model human information processing systems such as [97]; [98]; [99]. One of the most recognised and clear explanations of the human information processing model has given by Wickens [99]. This information model has been framed around five key components: (i) initial sensors (eyes, ears), (ii) perception, (iii) human memory (working and long-term memory), (iv) decision and response selection, and (v) response and execution. According to this model, as shown in Figure 14, the start point of the information process is the initial sensors, namely eyes and ears. The human brain then processes the detected information. Working memory is a short-term (recent) memory that maintains some amount of information in mind to enable its manipulation for further information processing while long-term memory is used for storing information and knowledge. The processed incoming information can be temporarily stored and manipulated in the working memory for supporting the human decision-making process. This stage can be described as “main thinking” according to Wickens [99] and also connected with long-term memory where information and knowledge can be stored for more extended periods of time as seen in Figure 14. The most appropriate response, finally, can be executed and respectively, the decision can be made in the last stage. This information model of Wickens was adapted to operators by the current researcher. There are several essential factors, directly or indirectly involved with the decision-
making process of the operator in their working environment, such as the degree of attention, situation awareness, psychological conditions, experience, tacit knowledge, and skill.

Figure 14: The human information processing model presented by Wickens [99]

The current researcher improved this information model in accordance with the decision-making process of operators. The detailed explanation of the improved model will be given in Chapter 2. of this thesis in order to reflect how the information will be processed during the decision-making of operators.
Chapter 2

2 Developing a new operator’s models

2.1 Situation awareness and decision-making models

The operator makes decisions every day in many situations where s/he must have a selection of a course of action from among multiple alternatives. The decision-making process of the operator strongly depends on many factors, such as total load systems, mental condition, experience, tacit knowledge, and skills. Unfortunately, some decisions lead to the loss of lives of hundreds of people and have extraordinary economic consequences. On the one hand, the “situation awareness” and “decision-making” is the central element of the model, seen in Figure 15. This figure demonstrates the operator model [13]; [14] developed by adaptation of the well-known and probably the most used model created by Endsley [13]; [85]. According to this model, situation awareness is made at three different levels:

- Level 1. Encompass and awareness of specific critical elements of a situation,
- Level 2. Comprehension of a current situation, integration of that information in the light of operational goals,
- Level 3. An ability to project future states of the systems.

In this model, the situation is evaluated from the “present situation” instead of the state of the environment as defined by Endsley. Obviously, the “current situation” is continuously changing depending on the environmental effects (such as weather), real air traffic situation (including the individual aircraft performance), operator behaviours or working quality and applied controls. This operator model is improved, by the current researcher, by including the actual (present) mental condition of operators into the “individual factors” because, in the highly automated systems, the role of the psycho-physiological state of the operators is increasing. Moreover, another modification in this model is that operators apply “control actions” and then they face with new “present situation”. This model starts with a “present situation”; after having the “control action”, operators will have a new situation depend on the previous state, as seen in Figure 15. Depending on situation awareness, operators make decisions on how to control aircraft most safely. “Performance actions” do not only depend
on the skills of the operator but also highly dependent on human aspects including operator behaviour, practice, personal habits, personal characteristics (mental condition), physical and psychophysical conditions. For example, if an operator is tired or under being a stressful situation, the reaction time of the operator is increasing. Operators may know absolutely what to do in a situation; however, if s/he does not have enough practice and experience, then this would create an accident as well.

![Figure 15: The created model of situation awareness and decision making in future dynamic ATM environment (Source: Own Modified Version, [13]; [14]; [27])](image)

The (i) system functions, (ii) operational characteristics, and (iii) operator - system interface (working environment) compose the system factors. The developed model includes some new system factors as (i) system operability (including interoperability), controllability and automation, (ii) system operational intensity and (traffic) complexity, observability and operational (flight) information system, and (iii) improving the working environment of operators to increase the level of situation awareness. The underlined new element and incorporated into the traditionally applied situation awareness model adapt the model to the future air transport system, and future air traffic management. As it is investigated and well-known, the success of situation awareness and decision-making highly depends on human behaviour (skill and performance) and operator loads (work, task, information, communication and mental load). As Rasmussen ([100]; [101]) defined thirty years ago, the situation awareness and decision-making might be realized on three different levels. The first level, so-called “skill-based control” is applied by the operators when the situation is normal, and the operator can easily recognise the situations and can work “automatically”. At the second level, the operators
must recognise and identify the situation and apply the “rule-based” solutions to reach the expected situations. In case of abnormal flight situations or possible flight conflicts, the operators must derive the solution with their knowledge and practice. This level is called the “knowledge-based level”. The information model of Wickens [99] was improved and adapted by the current researcher, to operators by including (i) sensory memory, (ii) situation awareness, (iii) skill and competence, and (iv) load measuring techniques (Figure 16). According to this model, after receiving information by the operator senses, receptors encode stimuli from the external environment. Thereafter, the collected information might transmit through sensory memory which limited a certain amount of information that can be processed for a concise time, about half a second to three seconds and forwards to working memory. Finally, this information might be encoded and stored in long-term memory.

Figure 16: The improved model of human information processing and decision-making [99] (Source: Own Modified Version)

This information process highly depends on the operator’s skill, competence, experience, physical and physiological condition. On the other hand, the total load of operators can be monitored from their responses during “situation awareness”, “decision-making” and
“performance actions”. The information processing is linked with the reaction time of operators. Due to highly automated systems, information load increases some phases of flight such as take-off, approach, and landing particularly. It is, therefore, these flight phases that can generate high mental state which can, in turn, lead to increased “reaction time”, and reduced “decision-making time”. According to Cummings [102], a person is capable of processing three bits of information per second on average without error. In case if an operator receives higher than three bits per second, the occurrence of unavoidable errors and loss of information can be expected. However, the rate of information processing highly depends on operator’ characteristics such as operator skills, competence, experience, total load, physical and physiological condition.

2.2 Operators’ subjective decision

In today’s aviation technology, operators use “subjective decision”; namely, they apply subjective situation awareness, situation analysis and decision-making process in aircraft controls. In the case of an unforeseen situation, operators first must define the problem, choose, then, the solution from the set of resources and make a subjective decision. The resources can be classified into two groups; (i) “active resources” such as physical, intellectual, and psycho-physiological behaviours, and (ii) “passive resources” such as information, materials, and finance - aircraft control system in its physical form. There are many references and rules for taking into account the subjective characteristics of decisions. For example, Hilburn and Jorna [103] analysing the workload had explored both the subjective and objective workload of ATCOs. Another example: the pilot licensing is based on the subjective decision of the certified flight examiners [104]; however, nineteen flight parameters and seventeen statistical or mathematical metrics might be applied for objective evaluation of the operators’ technical skills [105]. The aircraft control system is subjective, endogenous, stochastic and active because of the human-operator: pilot or ATCO in a loop, who actively generates the control inputs, depending on the situation evaluation and decision-making. The control originates from inside the system (from operators), which means the system is endogenous. The decision of the operator per situation is dependent on knowledge, experience, skill, current mental state, physical condition, and awareness of the situation. Hence this is the so-called “subjective decision mechanism” [104]. The air traffic will be expected to increase significantly in the near future, the NextGen, SESAR and other international projects funded as a result of this volume increase. One can expect that with a significant increase in air traffic and congestions, “subjective decision-making” will have more effect on overall flight safety [34]. The current major ATM projects mainly focus on following terms; (i) improving the safety, (ii) reducing air traffic management costs, and (iii) reducing the environmental impact. Besides lowering the ecological impact, the other goals are
significantly related to the “subjective decision-making” of operators. The decision of operators depends on their situation awareness, practice, knowledge, and skills. The aircraft control system is stochastic, subjective, nervous (endogenous) and active system. The human in loop actively generates the control inputs depending on the operator actions (situation, evaluation and decision making) where his decisions are related to his nervous system. Obviously, the human operator makes a decision on his/her subjective analysis. These subjective analyses contain both active and passive resources. “Active resources” are known as psychical, psychophysiology, operator’s behaviour, possibilities of subjects while passive ones are known as finance, information, materials, information, the energy of aircraft (aircraft control system in its physical form), etc. ([13]; [106]).

![Figure 17: Operator subjective decision model [34]](image)

As seen in Figure 17, the operator collects the information about the situation of the “technical system”, $S_i$ that changes depending on the system performance and characteristics, environmental conditions, effects of other interacting systems and realised control (management). The operator first identifies and understands the situation, and then analyses the current situation and makes an appropriate decision while choosing the best option in decision-making, and finally applies performance action. During the decision-making process, the operator may select the choice on the set of the “possible actions”, $S_p$ including all the accessible or achievable devices, methods and factors. The operator, then, must identify “disposable actions”, $R_{disp}$, that might be applied in a given situation for controlling the system. Finally, the operator should choose the “required actions” $R_{req}$, that may move the system to the intended condition. Of course, this situation awareness and decision-making process realised by operator depends on the operator behaviours; namely on knowledge, skills, and experience of operators and its actual mental condition-actual physical, psychological condition. The operator’s decision, therefore, is subjective. In a more general
approach, the operator must activate its passive and resources and then applied physical controls and active resources [107]. The “passive resources” are the resources of the aircraft, while the “active resources” are related to the operator itself. The active resources are defined by the operator decisions, which also determine how passive resources will be used. In this process, the remaining time, until the last moment, while the decision must be applied plays the most crucial role. The required decision time is the sum of times of the “situation awareness”, “decision-making” and “performance actions”. The successful decision can be made if the remaining time would greater than the required time. In future systems, the operator subjective decision must be supported. The first step is to develop the methods of investigation and modelling the subjective decision processes. The developing methodology may use in a wide area of application, including even the distance control of unmanned aerial vehicles [108].

\[ c(t): \quad (x_0, t_0, \omega(t_f \in [t_0, t_0 + \tau])); \quad 2.1 \]

\[ R^{disp}(t_0), R^{req}(t_0), \ldots) \quad 2.2 \]

Or in a more general form:

\[ c(t): \quad (P: \sigma_0(t_0) \rightarrow \sigma_j(t_f \in [t_0, t_0 + \tau])) \quad 2.3 \]

\[ \in S_f \subset S_a, R^{disp}(t_0), R^{req}(t_0), \ldots) \quad 2.4 \]

where \( x_0 \) is the vector parameters at the initial state at \( t_0 \) time; \( x_0 \) gives the state of the system in the given time; \( \tau \) defines the available time for the transition of the state vector into the set of \( \omega \) not later than \([t_0, t_0 + \tau]\); \( P \) is the problems how to transit the system from the initial state into the one of the possible \( S_f \subset S_a \) not later than \( \tau \). On the other hand, the quality of the operators’ work might be described as with active resources \( (R^{req}_a) \) that defines how passive resources \( (R^{req}_p) \) are used [93]. Other analogical possible characterisation might be given by the velocity of utilisation of the active resources.
Figure 18: Operator decision – action process (endogenous dynamics) in aircraft operation (control) system (left), Situation chain of operational aircraft process as a result of an active subjective endogenous control (right) [55]

\[ V_{a}^{req} = f_{v} V_{p}^{req} \]  \hspace{1cm} 2.5

\[ V_{a}^{req} = \frac{dR_{a}^{req}}{dt}, V_{p}^{req} = \frac{dR_{p}^{req}}{dt} \]  \hspace{1cm} 2.6

where,

\[ f_{v} = \frac{\partial R_{a}^{req}}{\partial R_{p}^{req}} \]  \hspace{1cm} 2.7

The operator must have time \( t^{req} \) to understand and evaluate the given \( \sigma_{k} \) situation \( t_{ue}^{req} (\sigma_{k}) \), making-decision \( t_{dec}^{req} (S_{a}) \) that intends to transit the situation process from \( S_{k} \) state into the \( S_{a} \) and the required time to perform the action \( t_{react}^{req} (\sigma_{k}, S_{a}) \):

\[ t^{req} = t_{ue}^{req} (\sigma_{k}) + t_{dec}^{req} (S_{a}) + t_{react}^{req} (\sigma_{k}, S_{a}) \]  \hspace{1cm} 2.8

The subjective factor of operators might be defined upon the ratio of the required and disposable resources:

\[ r_{k} = \frac{R_{k}^{req} (\sigma_{k})}{R_{k}^{disp} (\sigma_{k})} = t_{k} = \frac{t^{req} (\sigma_{k})}{t^{disp} (\sigma_{k})} \]  \hspace{1cm} 2.9

In this case, an endogenous index \( (\varepsilon_{k}(\sigma_{k})) \) can be defined as:

\[ (\varepsilon_{k}(\sigma_{k})) = \frac{r_{k}}{1 - r_{k}} = \frac{t^{req} (\sigma_{k})}{t^{disp} (\sigma_{k}) - t^{req} (\sigma_{k})} \]  \hspace{1cm} 2.10
\[
(\varepsilon_k(\sigma_k)) = \frac{t^{req}(\sigma_k) + t^{dec}(S_a)}{t^{disp}(\sigma_k) + t^{dec} - t^{req}(\sigma_k)} \tag{2.11}
\]

where \( t^{dec}(S_a) \) is the time required to recognise the set of alternative strategies.

Naturally, we can assume that controllers are able to evaluate the consequences of their decisions and, therefore, they can determine the risk of the applied solutions. Such evaluation can be defined as the subjective probability of situations: \( P(\sigma_k) \), as the distribution of canonic assemble of the preferences is assumed to hold the following form

\[
p(\sigma_k) = \frac{p^{-\alpha}(\sigma_k)e^{-\beta\varepsilon_k(\sigma_k)}}{\sum_{q=1}^{2} p^{-\alpha}(\sigma_q)e^{-\beta\varepsilon_k(\sigma_q)}} \tag{2.12}
\]

where \( p(\sigma_k) \) describes the distribution of the best alternatives from a negative point of view. The time-depending coefficients \( \alpha \) and \( \beta \) should be selected in a way to model the endogenous dynamics, model the subjective psycho-physiological personalities of the operators. The qualities of the controller highly depend on different factors including "periodical" incapacity, to make the decision time, such as landing or go-around.

Equation 2.12 has unique features: in the case of \( t_k = \frac{t^{req}(\sigma_k)}{t^{disp}(\sigma_k)} \to 0 \) preferences are determined by the subjective probability \( P(\sigma_k) \), and in case \( t_k \to 1 \), the preference turns into zero. Equation 2.12 comes from the solution of the following function:

\[
\phi_p = -\sum_{k=1}^{N} p(\sigma_k)lnp(\sigma_k) - \beta \sum_{k=1}^{N} p(\sigma_k)e_{k}(\sigma_k) \tag{2.13}
\]

\[
-\alpha \sum_{k=1}^{N} p(\sigma_k)lnP(\sigma_k) + \gamma \sum_{k=1}^{N} p(\sigma_k) \tag{2.14}
\]

A special feature of this function is that the structure of the efficiency function includes the logarithm of the subjective probability.

\[
\eta_p = -\sum_{k=1}^{N} (\alpha lnP(\sigma_k) + \beta \varepsilon(\sigma_k))p(\sigma_k) \tag{2.15}
\]
The complexity of decision-making could be characterised by the uncertainties or the operators’ incapacity to make decisions, which is increasing while getting closer to the minimum decision altitude, $H_{DMI}$. To make decisions, operators must overcome their “entropic barriers”, $H_p$. The rate of incapacity could be defined with the norm of entropy.

$$H_p = \frac{H_p}{\ln N}$$

2.16

There is not enough information on the physical, systematic, intellectual, and psychophysiology characteristics of the subjective analysis, on the way of thinking and making a decision of subjects-operators. Only limited information is available on the time effects, possible damping the non-linear oscillations, and long term memory. Professor Kasyanov described a simplified decision-making process at the final phase of the aircraft approach in [93]. In Figure 19, the set of alternative situations were given by $t_0, x_0, S_a: (\sigma_1, \sigma_2)$ with the distribution of preferences $p(\sigma_k)$ where $\sigma_1$ indicates the landing and $\sigma_2$ defines the go-around.

![Diagram](image)

*Figure 19: Final phase of aircraft approach [93]; [106]*

The preferences are oscillating, because of the exogenous fluctuation (while decision altitude is getting closer) and the endogenous processes (depending on the uncertainties in the situation awareness and operators-pilot incapacity to make decisions). If pilots are able to overcome their entropy barrier up to command for go-around (reaching the decision minimum altitude), $t^*, x^*$ then they could make a decision. Due to this decision, the set of situations, $S_a$, can be given with the followings:
If pilots are not able to overcome their entropy barrier before reaching $t^*$, $x^*$ the flight situation would become more complex, and therefore the possibility to perform a go-around (case $\sigma_2$) might be even out of the possible set of situations. A special chaotic model was introduced by Professor Kasyanov [93] based on the modified Lorenz attractor [109] for modelling the endogenous dynamics of the described process.

\[
\frac{dX}{dt} = aY - bZ - hX^2 + f(t); \quad 2.17
\]

\[
\frac{dY}{dt} = -Y - XZ + cX - mY^2; \quad 2.18
\]

\[
\frac{dZ}{dt} = XY - dZ - nZ^2 \quad 2.19
\]

Here $a$, $b$, $c$, $d$, $h$, $m$, $n$ represent the constants while $f$ takes into account the disturbance. In the case of $h=m=n=0$ and $f(t)=0$, the model turns into the classic form of Lorenz attractor. In this model, the coordinates of attractors can be defined as $X$ – the inner endogenous parameter, $Y = \beta$ and $Z = \alpha$. According to [110] and [111], no strong arguments are explaining the use of Lorenz attractor to model the human way of decision making (human thinking) [110]; [111] however, the results of the application are close to real situations.

Professor Kasyanov and Professor Jozsef Rohacs investigated various model types, and evaluated the model parameters [93]. The following values are recommended for a medium sized aircraft (weight of aircraft, $W = 106$ N; wing area, $S = 100$ m$^2$; wing aspect ratio $A = 7$; thrust $T = 9.4 \times 104$ N; and velocity $V = 70$ m/sec): $a=8$; $b=8$; $c=20$; $d=43$; $f=0.8$; $h = 0.065$; $m = 0.065$; $n = 0.065$. Using these parameters, the subjective probabilities might be chosen as $P(\sigma_1) = 0.53$, $P(\sigma_2) = 0.6$ and $\epsilon_1 = 5.5 + 0.01t$, $\epsilon_2 = 5.4 + 0.04t$ take into account the decreasing difference in the required and the available time for the decision. This described model applied and tested in the EU FP7 PPlane Project ([106]; [112]; [113]) to determine the requirements of safe landings related to personal planes pilots, so-called less-skilled pilots. In this research, a simulation model was created, by the current researcher, by the modified Lorenz attractor on MATLAB for the subjective decision-making of the pilots in different level
of expertise, namely (i) student pilot, (ii) less-skilled pilot, (iii) experienced pilot and (iv) well-experienced. Chaotic Lorenz’s model was introduced for describing the way of thinking of pilots during the final approach. The virtual parameters and model were used based on the real measured characteristics of pilots. This model was used for investigating go-around and landing situations during final approach (Table 2).

<table>
<thead>
<tr>
<th>Student Pilot</th>
<th>Less-skilled Pilot</th>
<th>Experienced Pilot</th>
<th>Well-experienced Pilot</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: 6</td>
<td>A: 8</td>
<td>A: 10</td>
<td>A: 12</td>
</tr>
<tr>
<td>B: 6</td>
<td>B: 8</td>
<td>B: 10</td>
<td>B: 12</td>
</tr>
<tr>
<td>C: 10</td>
<td>C: 20</td>
<td>C: 35</td>
<td>C: 45</td>
</tr>
<tr>
<td>D: 0</td>
<td>D: 0.43</td>
<td>D: 1</td>
<td>D: 1.2</td>
</tr>
<tr>
<td>f: 1.3</td>
<td>f: 0.8</td>
<td>f: 0</td>
<td>f: 0</td>
</tr>
<tr>
<td>H: 0.065</td>
<td>H: 0.065</td>
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<td>M: 0.065</td>
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<td>$P(\sigma_1)$: 0.53</td>
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<td>$P(\sigma_2)$: 0.6</td>
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</tbody>
</table>

Table 2: Flight parameters of pilots (Source: Own Edition)

The results of using the described model for four different levels of pilots are shown in Figure 20. The results demonstrate the chaotic character of the decision-making process for go-around and landing, which can vary depending on the level of experience of pilots.
Figure 20: General 3D model of pilots way of thinking and decision-making process for four different levels of pilots (yellow: student, blue: less-skilled, orange: experienced and purple: well-experienced pilot) (Source: Own Edition)

According to these results, the final decision-making time and hesitation frequency are increasing while the level of experience is decreasing. In other words, student and less-skilled pilots are not able to make their final decisions easily in which situations create chaotic orbits seen in Figure 21. The final decision time of the pilots can be calculated from these results by checking when s/he will not have any hesitation between landing and go-around. The final decision is made when the probability of a specific situation (landing or go-around) gets stable.
Figure 21: Results of using the developed model to landing by four different levels of pilots (Source: Own Edition)

- If the parameters are set to a:6, b:6, c:10, d:0 f: 1.3, H: 0.065, M: 0.065, N: 0.065, $P(\sigma_1)$: 0.53, $P(\sigma_2)$: 0.6 for student pilot (Table 2), the entropy would quickly decrease, the hesitation is very high, and the final decision was taken in about 7 seconds (Figure 22).

- If the parameters are set to a:8, b:8, c:20, d:0.43 f: 0.8, H: 0.065, M: 0.065, N: 0.065, $P(\sigma_1)$: 0.53, $P(\sigma_2)$: 0.6 for the less-skilled pilot (Table 2), the entropy would decrease, the hesitation is still very high, and the final decision was taken in about 6 seconds (Figure 22).

- If the parameters are set to a:10, b:10, c:35, d:1 f:0, H: 0.065, M: 0.065, N: 0.065, $P(\sigma_1)$: 0.53, $P(\sigma_2)$: 0.6 for the experienced pilot (Table 2), the entropy would be decreased, the hesitation is reasonable, and the final decision was taken in about 2 seconds (Figure 22).

- If the parameters are set to a:12, b:12, c:45, d:1.2 f:0, H: 0.065, M: 0.065, N: 0.065, $P(\sigma_1)$: 0.53, $P(\sigma_2)$: 0.6 for student pilot (Table 2), the entropy would quickly be decreased, the hesitation is optimum, and the final decision was taken in about 1 second (Figure 22).
Figure 22 demonstrates the chaotic Lorenz model for the subjective decision of pilots during landing (Figure 22, left) and go-around (Figure 22, right). According to the results, the less-skilled pilot makes his final decision in 6 seconds while the experienced pilots make in 2 seconds. These outcomes show that less-skilled pilot needs 3 times more decision-making time between landing and go-around. This model is well usable for the investigation of the endogenous dynamics of the pilot decision-making from different skills and experience. The result of the research suggested that 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 levels of pilots while checking their way of thinking and decision-making process.

2.3 Operators’ new model

Another approach can be applying to the description of the operator model based on the operator loads. As discussed earlier, one of the most recognised and well-known load models described by Endsley. However, with the changes in the role of operators from active control to passive monitor, there is a need for redesigning this load model. The Endsley load model, therefore, was improved, by the current researcher, by including information load and its connections. The created model contains work, task, information, communication, and mental load, as seen in Figure 23. The task load is generated by the number and hardness of tasks to be solved by operators. It highly depends on airspace demands, interface demands, traffic
regulation, airspace design, traffic planning, and weather condition. In the case of highly automated systems, the changes in traffic intensity, abnormal and the emergency situation may generate several extra tasks. In the early days of aviation, operators received almost all flight information through his or her own observation of the world. As an operator workplace environment (cockpits, towers) become increasingly complex, the amount of information gained from aeronautic systems is also increased. The information load is applied for characterising a relatively new problem, initiated by supporting the operators with too many and partly not harmonised information from the different sources. For example, weather forecast information and weather conditions reported by pilots in the same sector. This situation confuses operators, and putting them into a difficulty to evaluate the right and required information. The information load, therefore, was created and included in the Endsley load model by the author. The information load depends on air traffic regulation, airspace design, traffic planning, weather condition and other aspects (such as unlawful actions, being under unforeseen or emergency situations).

![Image]

Figure 23: The new operator load model (Source: Own Edition [13]; [23]; [114])

The task and information loads together with real traffic complete the workload of the operators. This is the most well-known and applied merit. For example, Endsley and Kiris [115] developed a special “Situation Awareness Global Assessment Technique” (SAGAT) that is used nowadays by Next-Gen and SESAR. Other well-deployed measuring and evaluation methods are the “NASA Task Load Index” (NASA-TLX) [116] and “Situation Awareness Rating Technique” (SART) [89]. These old methods are improved and combined by new technologies permitting to measure the human performance to evaluate the future ATM, or future automation concepts, see for example “Automation Thrust Index” (SATI) [117] or identifying the critical human performance [118]. Communication load is the level of understanding between operators which depends on language, cultural norms, and social relations.
Communication load, therefore, included in the Endsley Load Model as well. Workload depends on real traffic conditions, and traffic complexity, etc. and it can be determined from the traffic performances, (for example [84]) or evaluated from the operator reactions for example from the evaluation of the ATCOs voice, (for example [85]). Finally, the actual physical and psycho-physiological condition called a mental load can be defined and measured. This load depends on human aspects: human behaviours, skills, knowledge, tacit knowledge, practice, physical condition, and psychophysical condition. The mental load plays a determining role in the so-called subjective situation awareness and decision-making of operators [13]; [14]. In the literature, numerous articles published in the field of mental load. Furthermore, most of these articles wrote by instead of engineers than psychologist and medications. The mental load is associated with the physiological situation of operators. The mental load of operators, therefore, measured by the current researcher by using medical and physiological devices. With the rapid technological changes, in many cases, information, communication and mental load became potential problems that required aviation systems to monitor and control. Therefore, these load systems were defined separately in the model seen in Figure 23. By this way, operator load is separated into five groups, namely work, task, information communication, and mental load which called as operator total load. The total load monitoring and management systems are created and tested in a flight simulator.

2.4 A further aspect of the operator model

As discussed in Chapter 2 that one of the most prominent examples of human factors in aviation is language and culture. Communicating effectively via the radio in aviation is a challenging task for most pilots and ATCOs. This is even more challenging for non-native English speaking operators. Pragmatic errors are causal factors in failures within the air traffic system. Pilot and ATCOs make an appropriate decision based on the message which is received over radiotelephony. Sometimes operators, particularly non-native English speakers, fail to convey intended messages to ATCOs or other pilots who might result in serious misunderstanding. In order to have efficient and successful radio communication between operators, all the messages must be conveyed, received and interpreted clearly. Pragmatic failure in aviation communication might lead to many aircraft crashes and incidents while cruising and on the ground. Operators make communication mistakes and, due to the dynamics of the system, these mistakes can be severe. In comparison to many other threats to aviation safety and security, pragmatic failure in aviation communication and cultural misunderstanding can be more challenging to avoid. The reason is, pilots and ATCOs are neither in face-to-face contact nor have a video speech interface between them while communicating with each other. Their communications are conducted entirely through radio
messages using a specialised language designed to make communication as accurate and efficient as possible [72], [73]. Therefore, their sense of listening and speaking play a very important role. According to Sauer [74], the gesture is, at the same time, a noun and a verb. Therefore, even if operators use the same language and want to convey the same messages, the interpretation of the messages sometimes can be different depending on the hearer due to the same factors such as incorrect communication, cultural norms, social relations, etc. In aviation communication, ideally, operators have to try to communicate without any pragmatic meaning. That is theoretically impossible, but the aim is to minimise how much pragmatic information is conveyed. Any pragmatics can cause misunderstanding. There can always be misunderstandings because one of the operators can interpret the context differently. When speakers communicate pragmatically, they want to make sure that they have the same understanding of the contexts as the speaker. The more you understand someone, more you can speak with pragmatics, because you will understand the context better. Also if you are having a conversation, and if it is not a critical conversation, you have all the time to talk back and forth in order to understand the meaning better. If you have enough time you can clear up any temporary misunderstandings that are caused by pragmatics. Therefore, pragmatics is very dangerous in aviation communication because there is usually not enough time (particularly in abnormal or emergency situations). A questionnaire was conducted in order to investigate the reasons for communication errors of operators (pilots, ATCOs) related to several factors such as cultural norms, regional accents and poor language skill. The aim of the survey is to find a way to avoid pragmatic failure in aviation communication. The data were collected from questionnaires which were completed by pilots and ATCOs, including professional pilots of domestic and international flights (experienced pilots), student pilots (less-skilled pilots) and ATCOs in air-traffic service units that handle domestic and/or international flights and retired ATCOs. The survey took most participants between 10 and 15 minutes to complete.

The questionnaire used in this research consists of 21 questions, some with multiple choices, a multiple-choice grid, and short answers. These questions can simply be divided into four parts; (i) Q1-Q9 (ii) Q9-Q16, (iii) Q16-Q19 and Q20-Q21.

- The goal of the first part of the questionnaire is to gather general information about operators, including gender, age, job (pilot or ATCO), years of expertise, etc.
- The second part of the questionnaire assessed cultural differences and their effect on communication.
- The third part of the questionnaires was developed to investigate the reasons for misunderstandings between operators over the radio.
- The last two questions allowed operators to freely express their views on how native and non-native English speakers can improve their communication over the radio.

This questionnaire is based on 212 responses of operators: 168 ATCOs (79.2%) and 44 pilots (20.8%). The majority of the participants who completed the questionnaire were men (183 participants – 79.7%), i.e. 142 air traffic controllers and 41 pilots (Figure 24, left). Some of the operators have indicated more than one profession in the survey (both pilot & ATCO, pilot & ANSP-Air Navigation Service Provider Director, ATCO & AFIS - Aerodrome Flight Information Service director, and Pilot & Engineer). The mean age of the operators was 38.4, with a range of 18 to 81 years: 51.4% of the participants (109 operators) were between the ages 24.6 and 37.8 (Figure 24, right). This shows that the survey was filled in by a range from student operators to retired operators, which plays a very important role in the accuracy of the results.

Figure 24: Gender of operators (left) and age of operators (right) (Source: Own Edition [71])

The flight experience of the surveyed pilots ranged from less than 50 to more than 5000; the majority of the pilots (82.7%) have flight hours between 100 and 5000 (Figure 25, left). On the other hand, the experience of the surveyed ATCOs ranged from 5 months to 42 years; the mean experience of the ATCOs was 14.9. The experience of the 80 ATCOs (47.6%) was between 5 months to 11.25 years (Figure 25, right).

Figure 25: Flight hours of the pilots (left) and Experience of the ATCOs (right) (Source: Own Edition [71])

The design of the survey was to be demographically inclusive and worldwide accessible. There were operators from 69 different nationalities, listed in Figure 26. Hungarian, Indian, Turkish,
Nigerian, Australian and American had the six most significant portions (number of operators: 19, 19, 15, 13, 8 respectively).

The majority of surveyed operators are non-native English speakers (80.9%), while only 19.1% are native speakers (Figure 27, left). Although 40% of the survey respondents reported having a Level 5 Aviation English score, only 11.4% have not been tested yet (Figure 27, right).

In the second part of the questionnaires, a database was built with information about: the culture of operators, measuring the understanding between native and non-native English speakers of the operators, problems with the current ICAO Standard Phraseology, the cultural effect of operators in radio communications, etc. When operators are asked “Do native speaking pilots and ATCOs generally speak aviation English to non-native speakers in an effective manner”, they mostly answered “Usually” (127 Operators – 59.9%) (Figure 28, left). When asked “Should native speakers speak Aviation English to non-native speakers in the same way as they speak Aviation English to other native speakers”, they mostly have answered “Yes” (132 operators – 62.2%) (Figure 28, right). Moreover, only 10 operators have given a short answer to this question. From this group, some of the operators believe that there should be more “consideration” from the non-native speakers. This means that if a native...
English speaker of operator feels that non-native English speaker of operator has difficulty using and understanding English, then the native English speaker needs to slow down his/her speech rate, avoid using slang, idioms, jokes and references specific to their own culture while delivering their messages in order to not leave room for confusion and ambiguities.

Figure 28: “Do native speaking pilots and ATCOs generally speak aviation English to non-native speakers in an effective manner” (left) and “Should native speakers speak Aviation English to non-native speakers in the same way as they speak Aviation English to other native speakers” (right) (Source: Own Edition [71])

When operators were asked “Are you satisfied with the ICAO Standard Phraseology”, happily, over 89.8% of the surveyed operators are satisfied with the current ICAO Standard Phraseology. Unfortunately, 10.2% of the operators believe that some of the standards need to be modified for clear and unambiguous communication over the radio (Figure 29). Their satisfaction with the ICAO Standard Phraseology is extremely important to communicate effectively over the radio; regardless of whether they are native or non-native English speakers.

Figure 29: “Are you satisfied with the ICAO Standard Phraseology” (Source: Own Edition [71])

According to the surveyed operators, some suggestions can be given in order to improve the ICAO Standard Phraseology:

- There is a lack of vocabulary in ICAO Standard Phraseology for contingency and emergency phases. It should contain a specific phraseology for the most frequent unusual situation in order to minimize the risk of misunderstanding between pilots and ATCOs.
• Most of the operators do not use the word “to” in “descend to Flight Level”, “climb to Flight Level”. The word “to” still creates confusion as it is a homonym for “two”, “to” or “too”.
• Phonetics should be emphasized in teaching Aviation English to avoid ambiguity in a speech where there is difficulty in deciphering words by either pilots or ATCOs; difficult words should be spelt out using the ICAO alphanumerical.
• ICAO Standard Phraseology should be simplified to reduce RT (Radio Telephony) congestion.
• There is a need to be more flexible in order to improve understanding between pilots and ATCOs.
• Some of the surveyed operators commented that ICAO constantly changes words. However, these words are not the ones that create confusion and ambiguities.

With regard to the result of the survey, all of the operators agree that good communication has significant effects on teamwork effectiveness and safety (Figure 30). It is obvious that communication plays a great role in the culture. Cultural differences might cause communication problems in an aviation environment. In order to avoid cultural misunderstandings, operators should understand the cultural norms and values of another operator. Cultural differences can also lead to differences in pragmatic meaning. Semantic meaning can be thought of as the “dictionary meaning”. (It would be practically impossible to create a dictionary with all possible pragmatic meanings as it would need to take into account all possible contexts.). The messages in aviation would be more explicit when the pragmatic meaning is avoided, as in theory, every language learner has access to the same “dictionaries”, regardless of their culture.

![Figure 30: Statements on the culture of operators (Source: Own Edition [71])](image)

The aim of the question below (Figure 31) is to find some reasons for misunderstandings between native and non-native operators. Seven different statements were given to the survey participants. According to the results, native English speaking operators speak too fast and
use complex words and structures. It is also necessary to highlight that non-native English speaking operators misunderstand some of the words from native English speakers that sound the same as other words (homonyms).

Figure 31: Statements on native – non-native English speakers (Source: Own Edition [71])

Misunderstanding in aviation remains a serious threat to safety. As discussed in the second chapter, 80 per cent of aviation incidents or accidents can be traced to incorrect communication. The reason for the communication errors between pilots and ATCOs can be mainly attributed to poor language skills, heavy foreign accents, and failure to use ICAO Standard Phraseology, etc. which results in misinterpreting the message over the radio. In order to avoid pragmatic failure as much as possible, operators need to know which factors affect the meaning of the context such as cultures, values, norms, religion, social background, etc. All these factors can vary from person to person, and these differences can also assign inaccurate meanings to words. As a result, greater importance should be attached to pragmatics. When asked, “How many times have you experienced misunderstanding that has been quickly cleared up?”, the majority of the surveyed operators (33.2%) answered more than 10 (Figure 32, left). And when asked “How many times have you experienced misunderstanding that has not been quickly cleared up?”, the majority of the operators (40.6%) answered between 1 to 3 (Figure 32, right). This result shows that serious misunderstandings are still happening in aviation communication.

Figure 32: How many times have you experienced misunderstanding that has been quickly cleared up? (left) and How many times have you experienced misunderstanding that has not been quickly cleared up? (right) (Source: Own Edition [71])
When operators asked “Please write three things that native English speakers can do to improve communication with you on the radio”, they answered the biggest five issues as (i) Maintain rate of the speech, (ii) Using ICAO Standard Phraseology, (iii) Use simple structure, (iv) Speak clearly, and (v) Not using slang/jargon/expression/dialect (Figure 33).

Figure 33: Please write three things that native English speakers can do to improve communication with you on the radio (Source: Own Edition [71])

When operators asked “Please write three things that Non-native English speakers can do to improve communication with you on the radio”, they answered the most significant five issues as (i) Using ICAO standard phraseology, (ii) Maintain rate of speech, (iii) Improve English skill, (iv) Clarify in case of a doubt/verify when necessary, and (v) Listen carefully (Figure 34).

Figure 34: Please write three things that Non-native English speakers can do to improve communication with you on the radio (Source: Own Edition [71])

Automation essentially relocates and changes the nature and consequences of human error, rather than removing it. 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: For native speakers: (i) should be taught how to communicate simply and precisely with their non-native speaker colleagues, (ii) speak at a correct speech rate, (iii) speak clearly and concisely, (iv) and not use slang, idioms, dialects or jokes. For both native and non-native English operators: (i) follow strictly the ICAO Standard Phraseology, (ii) be familiar with different cultures, (iii) speak slowly and clearly to avoid misunderstandings, (iv) if the message unclear, ask for clarification to not leave any room for confusion, (v) exclude irrelevant information. For non-native English speakers (i) improve English and terminology, (ii) learn to articulate and (iii) talk in a calm and precise manner.

2.5 Measurability of the different loads

It is undoubtedly true that automation can bring benefits of improved performance and efficiency in aviation systems. Modern technological aeronautical systems are shifting the operator’s role burden qualitatively to a psychological level, rather than a physical one. One of the primary purposes of automation is to reduce operator loads, thereby improving performance and safety. However, this current technological state introduces a plethora of new concerns and problems such as information and mental load. Due to rapid advances and innovation in information technology, the use of load measuring devices for operator load management has been rapidly increased. The rise of the info-communication technologies provided a perfect base to generate, monitor and analyse more data, than ever before in aviation history. This improvement allows researchers to develop and integrate load monitoring sensors [119]. Operators who are overloaded with work, task, mental and information, tend to commit more errors, yield poor accuracy, become frustrated, stressful, poor situation awareness, thus will result in poor decision-making and performance acting. With the increase in the level of automation, sometimes operators would have possible under load [120] especially work underload, which leads to high error rates, poor situational awareness, and attention loss again. However, in many domains, operator overloaded is a more severe issue than underloaded. To date, various techniques have been developed to predict and measure workload, task load, and mental load. However, as the early sections indicate, the information load model was the first time created by the author. The concept of operator workload is related to the concept of arousal and distinguished from the physical workload. According to NASA [120], four approaches to measuring workload have been proposed, (i) subjective measures (ii) indirect measures, (iii) performance measures (speed, accuracy, activity, and task analysis, and (iv) Physiological Measures (Hear Rate-HR, Heart Rate Variability-HRV, Evoked Potentials-EPs).
The task load is generated by the number and hardness of tasks to be solved. It depends on airspace demands, interface demands, traffic regulation, airspace design, traffic planning, and weather condition. In the case of highly automated systems, the changes in traffic intensity, abnormal and emergency situations may generate several extra tasks. NASA Task Load Index was one of the well-used task load measurement technique in which participants must subjectively rate their workload along six different workload sub-scales: mental demand, physical demand, temporal demand, performance, frustration, and effort [120]. Operators do not process as much visual information outside their working environment (cockpit or tower window) as in the early years of aviation but have to extract information from the instruments inside the working environment in order to manage the flight. From this perspective, the information load is applied for characterising a relatively new problem, initiated by supporting the operators with too many and partly not harmonised information from the different and multiple sources – for example, weather forecast information and weather conditions reported by pilots in the same sector. The mental load plays a determining role in the so-called subjective situation awareness and decision-making of operators. This load highly depends on human aspects: human behaviours, skills, knowledge, tacit knowledge, practice, physical condition, and psychophysical condition.

In this thesis, several mental load measurement techniques were created and applied by physiological measures such as eye-tracking, heart rate measurement, EDA (Electrodermal Activity) measurements, binoculars, and integrated microsensors and motion cameras.

**Eye-Tracking**: Eye-tracking is a technique whereby an individual's eye movement, visual attention, and focus are measured with a view to understanding where a person is looking at any given time and the sequence in which the person's eyes are shifting from one location to another. Eye-tracking has been gaining popularity around for over a hundred years [121]. Amongst researchers have been carried out for developing eye-tracking systems in different disciplines such as in reading ([122]; [123]), human-computer interaction ([124]; [125]; [126]; [127]), psychoanalysis ([128]; [129]; [130]; [131]) and overlearned task such as hand washing, tea making or even how people compose photographs with digital cameras [127]. In aeronautics, the first eye-tracking measurements were realized in flight and ATC simulations. Optical measurements were used; namely, video recorded by cameras mounted into the working environment in front of the operators, and/or on the headband. The head positions were measured by wearing special items by operators (ATCOs).

- Training of operators – pilots, ATCOs, (even maintenance staff) for supporting their self-learning and evaluate their working qualities,
- Monitoring the operators’ activity and mental conditions and,
- Use of eye-tracking in control.
According to Geratewohl, [132] eye is one of the most important sensory organs of a pilot which processes 80% of all flight information. Rayner [133] believes that examination of eye movement data is one of the best methods to analyse visual information processing. Just like many researchers, Ziv [134] states that optimal scanning behaviour is crucial to achieving better aviation performance. The eye movement of pilots was examined by Kilingaru [83], and Van De Merwe, Van Dijk, & Zon [135] for assessing situation awareness. Eye-tracking measurements result in aggregated metrics like fixation duration, dwell times, and Moving Average Time Windows (MAW). Such simplified measures are applied even nowadays (see for example, [136]). The results give information not only directly about the eye movements, but discover some special peculiarities of operators. Mainly with utilising the eye-tracking glasses in-flight/ATM simulator, four different measurements can be realised: (i) measuring the operator eye motions and attentions in various flight modes (landing, take off, cruise or so on); (ii) measuring the time-invariant processes (for example, changes in cases when the operators’ attentions are decreasing during long flights) and (iii) monitoring the operators’ activity and mental conditions, (iv) use eye-tracking in control; measuring and collecting critical information from operators for comparing them with information received from other sources. In order to understand the basic principles of eye-tracking usage on an automated flight deck, an eye-tracking device was developed and used under a set of scenarios, seen in Figure 35. Although the developed eye-tracker works correctly, the result of this process was not satisfied because of some missing fixations. Therefore, to be able to get better outcomes, TOBII eye-tracking device has been used in the flight simulator of a Piper Seneca 3 multi-engine aircraft throught some flight scenarios at the Department of Aeronautics, Naval Architecture and Railway Vehicles (VRHT) at Budapest University of Technology and Economics (BME). This research was done in cooperation with the Department of Ergonomics and Psychology at BME. There were four persons on-board namely a pilot, an instructor and two observers who control the systems. In this research, eye-tracking study lets a researcher to understand what a pilot is looking at while performing a task. With the interpretation of the results, the mental load of operators can be measured and managed. The results of the TOBII eye-tracking results will be given in the Chapter 3.
Eye movement measurement offers deep insights into human-machine interaction and the mental processes of pilots. The analysis has been used to reveal the status of mental load based on different aspects of ocular behaviours, such as the number of fixations, dwell time, and the dilation of the pupil.

**Heart Rate Measurement:** The heart is an active, hollow muscular organ about the size of a clenched fist and weighs about 310 grams. It acts as a pump that provides a constant flow of blood throughout the human body. Heart rate refers to how many times heart contracts and releases in a unit of time, usually per minute (bpm), and it is directly related to the workload being placed on the heart. Heart rate is controlled by the Automatic (involuntary) Nervous System (ANS), which is a part of the Central Nervous System (CNS). ANS uses two branches; the Sympathetic Nervous System (SNS) and the Parasympathetic Nervous System (PNS). The sympathetic nervous system releases hormones to accelerate the heart rate, such as stress situations [138]. According to the National Emergency Medical Association, a normal value of heartbeat rate for a human adult is between 60 to 90 beats per minute that depends on the individual, age, heart condition, body position (whether the person is sitting or moving), body size, emotions (under stress situation, surprise, happiness, anger, fear, sadness, and anxiety) and skin temperature [139]. This heart rate is much higher for babies than adults around 120 bpm [140]. This is because the babies have a smaller heart; therefore, their heart needs to beat much faster than children and adults in order to pump the proper amount of blood throughout the body. Worldwide scientific researchers have shown that when a person experiences a stressful event, it brings on a number of physiological changes, such as (i) increase in heart rate, blood pressure, and blood glucose, (ii) starts to breathe more rapidly, (iii) increasing alertness (hearing may become more sensitive), and (iv) may begin to sweat. The monitoring and analysing the heart rate of operators is one of the most promising measures in mental load detection. With the integration of heart rate monitor into the operator working environment, the mental load can be measured, monitored and managed in real-time. The
physiological parameters of operators can be collected with the help of such medical methods such as heart rate monitor/heart rate variability ([13]; [50]; [141]; [142]), ECG ([143]), EEG ([128]; [143]; [144]), EMG ([147]; [148]),. Heart Rate and Heart Rate Variability of pilots were used by Mansikka et al. during a real instrument flight rules proficiency test in an F/A-18 simulator as measures of pilot mental workload [142]. Professor Szabo Sandor Andras evaluated the stress reaction of the heart-brain axis by Heart Rate Variability parameters produced by Firstbeat Bodyguard 2 and adapted to real flight [149]; [141]. In addition to this, QRS Mid-frequency and R-R interval studies let researchers draw the stress level of operators. For example, a very clear relationship was found by Professor Lajos Izso [117] between the complexity of the task and observable mental effort. When the observable mental effort is high, the Mid-Frequency Power (MFP) is systematically low, and when the mental effort is high, Mid-Frequency Power (MFP) is systematically high, seen in Figure 36.

![Figure 36: Power Density Heart rate (Middle-Frequency Band) versus time in second][125]

In this research, the heart rate of the pilots was recorded through three flight scenarios with a heart rate monitor in the flight simulator of the VRHT at BME. The purpose of this study reported in this thesis was to show how pilots’ heart rate is affected by various flight factors through simulated scenarios. The more detail about the measurements and a Markov chain method in the analysis of pilots’ heart rate measurements will be given in Chapter 3.

**Electrodermal Activity Device (EDA):** Electrodermal activity (EDA) is the property of the human body that causes continuous variation in the electrical characteristics of the skin. It is a psychophysiological indicator of emotional arousal generated by the sweat glands. Mental stress, respiration, and psychological changes are the primary emotional activators that cause strong reactions to the human body. With the activation of any of these factors, the human
brain sends signals to skin to increase the level of sweating. Moreover, as a result, human skin reacts and becomes a better conductor of electricity. The measurement of electrodermal activity (EDA) has a long tradition starting in the 1800s [150]. With the recent improvements in technology, it has been increasingly used in a wide variety of studies related to psychology. EDA is an efficient indicator of arousal, reflecting the activity of the sympathetic branch of the autonomic nervous system [151]. Different characteristics of electrodermal activity are important psychophysiological indicators of the emotional state and studied extensively in adults [144] as well as infants [152]. The most widely considered property is the skin conductance, which can be quantified by applying an electrical potential between two points of skin contact and measuring the resulting current flow between them. EDA can be measured at the surface of the skin accurately and efficiently. The amount of sweat glands varies across the human body but is the highest in palmer surface, wrist area, forehead and soles of feet regions [153]. These places of the human body have the highest density of eccrine sweat glands that respond to the emotional stimuli. EDA devices, therefore, should be placed on these body parts where changes in sweat gland activity can be easily detected. Even if a person may not feel any sweat on the surface of the skin, EDA devices are able to measure the changes in electrical conductance. In this research, EDA measurement has been used to collect, monitor and store data from a pilot which the result will be shown in Chapter 3. EDA measurement can be used to monitor operator activity in real-time and collecting high precision data from operator skin. In this research, EDA changes of a pilot were monitored in real-time with Obimons EDA devices in a flight simulator through different scenarios and the changes in the EDA signals were demonstrated on a smartphone and tablet via Obimon Android Application.

**Binoculars**: Tower controllers use binoculars since the beginning of air traffic control. It is a simple tool to collect information from vast distances that cannot be acquired by other methods such as where eye-tracking techniques are not applicable. Different methods can be used to determine the position of equipment, i.e. motion tracking. A motion tracking system can provide information about the activity of the subject, and with the information provided by the system, the point of regards can be determined. By knowing the position of controller and the point of regard, relevant or in special cases, extra information can be provided to the subject. Unnecessary to use binoculars in a remote tower environment, however in such a large room, determination of a position of the subjects and detection of their movement will not be less relevant. A system using a method that can follow and determine the position of the binocular can track the controller’s movement in the control room and can determine the direction ATCOs’ head. The application of such a system can collect appropriate data on controllers’ activity that can be used by the load management and supporting system.
**Integrated Microsensors and Motion Cameras:** Microsensors and motion cameras can be used for developing the operators’ working environment to measure total load systems, thereby increasing the level of situation awareness and decision-making. In the interest of becoming familiar with pilots’ behaviour, a side-stick and a computer mouse with integrated sensors were built by [119]; [154] to measure pilots’ physiological conditions during flight tests in the flight simulator laboratory at the department of VRHT at BME. The developed side-stick can measure pilots’ heart rate, skin conductance, palm temperature and force applied on the handle by the help of the integrated sensors. The measured data can be sent to develop software [155] which saves with flight data together. It communicates via TCP/IP connection with a flight simulator and with sensors via a virtual serial port. The software gives secondary tasks to pilots to measure their free resource capacity to get information about the subjects’ workload and helps to find out the way to estimate the workload from measured physiological parameters. The software collects data and stores them. This method was used to measure the reaction time of operators through flight scenarios. However, it still needs further investigation in order to analyse the operators’ physiological parameters better. More detail about the developed systems and some of the results will be given in Chapter 3.
Chapter 3

3 Developing the load monitoring systems

3.1 Conceptual design of the operators’ load monitoring system

The new operator load monitoring and management concepts were developed separately for pilots and ATCOs in order to improve their working environment and decision support system. The decision support system of pilots has three layers: (i) ground controlling system, (ii) onboard central processing unit, and (iii) smart cockpit screen. The ground controlling system includes ATM, aircraft remote control, S/PATS support centre and S/PATS management. Onboard central processing unit contains (i) pilot load management, (ii) situation awareness, and (iii) decision support. The on-board central processing unit collects and analyses the available data, including the information provided by cooperating with other aircraft and ground systems. The cockpit screen provides (i) the four types of pilot loads (work, task, information, and mental load) are presented in forms of coloured lines (left-bottom side), (ii) the tasks of pilots are displayed (central part), (iii) advice of pilots are given in a text for (right bottom), and (iv), the screen contains the more than 180-degree view of ahead and side of the aircraft (upper hand). The view on the left and right sides are shown as synthetic vision pictures. The central view is the real view, but the head-up display shows the recommended flight path (in predicted tunnel forms) and gives some other recommendations, measured information (Figure 37). For example, the ground sensed information on the wind and wind shear under the landing trajectory. The supporting systems include all the possible methods that may help in reaching the better flight performance and better stability, flight dynamics and control characteristics of the aircraft. The recommended pilot decision support system is based on (i) environment, (ii) technology, and (iii) solution (software) developments.

The vision of the future cockpit is a good example for future pilots supporting concept [94], containing the following solutions:

- the developed cockpit could contain up to six colour displays for the following tasks:
  (i) digital reproduction of the basic flight instruments,
  (ii) coloured macro and micro weather visualisation (around the aircraft on the flight path) with a 3D depiction of complex weather patterns that identify the location of, e.g. wind-shear, lightning or storm cells:
flight advisory system with

(i) day – night visualisation of the aircraft surroundings,
(ii) artificial vision generated by advanced sensors, digital terrain databases, accurate geo- positioning, and digital processing to provide a clear 3D picture of terrain, obstacles, or runway,
(iii) automatic identification and alerts to threats regardless of weather, nature or human- built obstacles,
(iv) recommended flight path (for example with 3D-tunnel / predictor) visualization:

- flight navigational display to represent the flight routes on the general moving map based on macro data,
- condition monitoring and diagnostic system display,
- other supplementary displays for further goals not mentioned here such as the visualisation of the back or side surroundings, or the information in emergency situations.

![Diagram](image)

Figure 37: Functional model of the pilot decision support system (s. – sensors) (Source: Own Edition [14]; [27]; [50])
Notably, small/personal air transport should have a ground support centre as well. This centre collects and evaluates the available data provided by ATM, cooperating small aircraft and other services (like weather prediction). It has two important sections: (i) determination of the recommended flight trajectories depending on the traffic conditions, and (ii) conflict detection and resolution. For example, this may display ranking (prioritised) landing of different aircraft. Each aircraft may have an individually supported trajectory. The other task of the “ground supporting system” is the remote control centre. The remote control might be initiated by the ground or the onboard sub-systems in case of identified emergency situations.

![Figure 38: Future load monitoring and management design in the cockpit (Source: Own Edition [14]; [27]; [50])](image)

The demonstration of the pilot load monitoring and management concept can be seen in Figure 38. As seen in Figure 38 (left-bottom) that there are four types of operator loads which are presented by small colourful columns vary depending on the measured loads. The second part is the task zone which is associated with the air-ground communication and recommendations from pilots and air traffic. Finally, the third part is the advice part in which pilots receive all the necessary advice on the cockpit window from the ground (ATCOs, aircraft remote control centres, robot pilots on the ground) or the board (robot pilots or other aircrafts’ pilots). For example, with upcoming technologies, the traditional two pilot set-up will be reduced to one onboard and one robot co-pilot onboard or the ground. The advice which will come from these virtual robot pilots can also be shown on the cockpit window.
Another load monitoring and management concept were developed for ATCOs. According to the developed concept, the advanced ATCO working environment has three major novelties ([34]).

(i) *Three-layer information displays:* High-resolution interactive displays are applied for (i) visualisation of the live (real active) situation based on the radar, flight information and ground service data, (ii), displaying the available further information automatically on requirements of ATCOs that initiated by the visual attention detection, while (iii) the third layer is used for situation awareness and analysis,

(ii) *Load monitoring system:* This system shows the continuously measuring individual task-, information, work- and mental loads of individual ATCOs. Generally, this information is available for the given ATCOs; however, in case of overloads or underloads, the system is reporting to the control managers,

(iii) *Decision support system:* This system assists the ATCOs to perform their job as requested. The system has three subsystems. The first one is the load monitoring system calling the attention of the ATCOs on their load conditions and may advise the required actions. The second subsystem is the situation awareness - situation analysis - and decision support process with a developed subjective decision model. Finally, the third subsystem works as an emergency alert.

The developed ATCOs' working environment concept (Figure 39) has the following features:

- tower-less augmented reality or/and large display systems (for individual solutions),
- three-layer information including,
- live (active) radar and ground service information,
- information from automatic flight information system,
- other information packages (weather forecast, regulatory requirements),
- monitoring system and sensors to measure the ATCOs' condition.
As seen in Figure 40, there are several load monitoring devices integrated into the working environment of ATCOs such as eye-trackers, heart rate monitors, skin temperature sensors, motion tracking systems, load tracking seat cushions, etc. In this concept, on the one hand, all the physiological parameters of ATCOs will be monitored and stored in real-time, and the four types of loads will be presented respectively on their display. On the other hand, there will be a display for a task and advise, which helps to avoid misunderstanding between operators.
In the case of unbalanced load (overloads or underloads) or if the system detects any sharp changes in the ATCOs vital health parameter(s), the system will automatically be reported to the control managers and generate some suggestions to the ATCO such as changing the trajectory.

3.2 System elements and their integration into the working environment

**Use of integrated microsensors:** Microsensors can be used for improving the operators’ working environment to monitor operator loads. In order to measure the mental state of operators, some of their physiological parameters can be continuously measured through an integrated site-stick and computer mouse [150]. These integrated devices consist of a heartbeat counter sensor, skin conductance, skin temperature, and strain gauges to measure grasp force applied by operators on the handle (how hard operator holds a side-stick or computer mouse) (Figure 41). The heart rate measurement is based on photoplethysmography (PPG) using infrared photo LED and phototransistor placed next to each other in handle under the pilot’s index finger. The skin conductance sensor measures how sweaty the pilots’ palm is while the temperature sensor provides information about pilots’ skin temperature. In the Flight Simulator laboratory of VRHT at Budapest University of
Technology and Economics, a series of tests were performed to measure the characteristics of pilots having different skills. New computer software was developed by [155]; [156] to log data coming from the sensors, flight parameters, and the reaction time of the operators. Different operators with different skills and flight experience were tested in many flight situations with different stress levels to characterise the operators.

Figure 41: Integrated microsensors into a computer mouse and a side-stick (a.) skin resistance, b.) skin temperature sensors c.) heart rate sensor [155]; [154]

The general system layout can be seen in Figure 42. The mouse original USB connection is separated from the DAQ system; therefore, it is not necessary to modify anything (hardware or software) in the ATC workstation. The measured data are fed into a separated PC via a USB connector. A computer mouse was modified with integrated some microsensors in order to make it suitable for accepting custom sensors (Figure 41, middle). The optical heart rate sensor has been positioned on the right side of the mouse, on the place of the right thumb. The sensor consists of infrared led and transistor pair, which, with the corresponding electronic, can sense the blood pressure variation in the thumb, if it is positioned correctly. This investigation aims to collect all the critical information by sensing the operators’ health signs and storing them into a computer by the connection of a USB connector. This method has been used by [154]; [157] in the ATC/ATM simulation laboratory at BME. Similarly, these microsensors are actively used in hospitals to measure the heart rate of patients and the oxygen level of their blood.

Figure 42: General Layout of Load Monitoring System [155]
There is also an accelerometer which was located inside of the computer mouse. This system can measure the acceleration of the movement along three axes and also can provide information about how fast users move the computer mouse and how many times the operator grasps the mouse, and duration of usage. The raw data can be collected by an integrated microsensor mouse and ordered into the data acquisition module after that process, can be stored in a connected computer. Evaluation of data and processing part will be done in a connected computer. In order to measure the reaction time of pilots, flight tests were performed by different pilots [155]. In this measurement, a realistic flight scenario was developed according to the characteristics of available simulators. This scenario starts in the air at 2500 feet with constant airspeed. The pilot had to fly straight for a while at constant altitude and speed, and then s/he had to initiate a climb to a given altitude with constant speed. Level off at this altitude, and fly straight with constant airspeed. A few minutes later pilots were ordered to perform a 360 degree left turn at a given altitude with constant speed. This step was followed by a straight flight at the same altitude with the same airspeed. After few minutes later he was ordered to descend to 3500 feet, then approach the runway and land. The way of approach and place of final turn to the runway was on pilots’ discretion.

Figure 43: Altitude, flight heading and measured reaction times of one test flight [155]

Figure 43 shows one of the test flights of this experiment. In the first diagram, the blue line represents flight altitude over time, while the discrete green lines represent measured reaction time. All phases of the first flight scenario can be identified easily. In the second diagram, the blue line represents flight heading over time, and green lines represent reaction time. It clearly can be seen that during the change from one flight mode to another one causes a short term increase in reaction time. Initiation of climb or turn, recovery from turn to straight flight or
from descent to level flight cause a measurable increase in reaction time. When the pilot was initiated to a recovery manoeuvre from 360-degree turn to fly straight, his reaction time is significantly increased and reached to 12.5 seconds. The aural warning warned the pilot, but he ignored subliminally. The same happened many times to different pilots in spite of the chosen warning sound, which was very loud and annoying. In order to better understand the mechanism of this kind of behaviour requires medical experts involved in further investigations. In this experiment, the reaction time of the pilot shows about 1-second constant increase during landing comparing to average reaction time measured during straight flight. Furthermore, the deviation of measured times also increased during the landing phase. This situation results in a higher operator load that increases the likelihood of operator errors.

**Use of motion cameras in the flight simulator:** There have been installed two motion cameras in the flight simulator cockpit by the current researcher. The main aim of the investigation is to demonstrate the difference in eye motion changes through different flight scenarios and to compare the differences between the experienced pilot and less-skilled student pilot.

![Flight simulator instrument panel](image)

Figure 44: The flight simulator instrument panel of the department of VRHT at BME (Source: Own Edition [13]; [137])

According to National Transportation Safety Board report in 2014 [158] and Federal Aviation Administration report in 2012 [159], approximately 80 per cent of all aviation accidents are related to operator errors, and the majority of these accidents occur during landing (24.1 per cent) and take-off (23.4 per cent). The eye movements and visual attention measured made by the experienced pilot and less-skilled student pilot in a flight simulator during take-off (Figure 45, left) and final approach (Figure 45, right). The measured eye motions were somewhat different depending on the tasks and skills of the pilots.
As can be seen in Figure 46 (left) that experienced pilots during take-off looked at the flight instruments longer than less-skilled student pilots. However, both of the pilots scanned the flight instruments more than looking outside of the cockpit, which is the proper way to do it. During landing phases, the experienced pilot looked outside of the cockpit significantly longer than the less-skilled pilot (Figure 46, right). In this case, both of the pilots looked outside of the cockpit more than looking at the flight instruments.

There is some central part of the instruments on a cockpit flight panel where pilots mainly look at them more frequently in a particular task, such as landing and take-off. The change of eye motions of pilots mostly depends on the following factors, (i) phase of a flight, (ii) task complexity, (iii) skill and experience of pilots, (iv) the level of operator loads (task, information, work, and mental load), (v) weather conditions, and (vii) unforeseen/emergency situation, etc. Based on the eye movement results, the handling pilot of an aircraft, during the take-off process, looks at a runway more than the flight instrument panel to keep aircraft on the centerline. Moreover, after the pilot often scanned the airspeed indicator, primary flight displays and navigational display (Figure 47).
The handling pilot of aircraft, during the landing process, mainly scans the airspeed indicator and runway. It is necessary to fly at low speed during descent; therefore, pilots must be kept the final approach speed at a required level. As seen in Figure 47, a less-skilled student pilot cannot divide his attention well between the inside and outside of the cockpit. This is because the interpretation of the instruments was taken longer for the less-skilled pilot than experienced one. If a pilot flies in a particular task (like performing a turn), some instruments get the priority to scan more frequently such as the artificial horizon, which provides information about the position of the aircraft, altimeter and airspeed indicator.

Figure 47: Eye movement comparison in the flight instrument panel for professional pilot and student pilot during take-off and landing (1: Airspeed indicator, 2: Artificial horizon, 3: Altimeter, 4: Torque, 5: Propeller RPM indicator, 6: Looking at the runway) (Source: Own Edition [13]; [137])

Given the importance of eye movements for visual perception, there has been a surge of interest in eye movements with numerous studies being conducted to clarify what kind of information can be derived from eye movements. A number of studies have suggested that eye movement, blinking rate, and fixation duration can be linked to the task, information processing, stress level, fatigue and loads [160]; [161]. Many investigators have reported that an increase in eye movement when the task increases in difficulty [162]; [163]. Rui Fu et al. [162] reported that as the complexity of the task increases, an operators mental load increases, which leads to an increase in eye movement of operators. However, some investigators have reported otherwise; they found, an inverse relationship, a decrease in eye movement with task
difficulty. For example, May et al. [164] indicated that eye movements were restricted as counting complexity increased. When the level of task difficulty increases, the total load of operators is also increasing, mainly work, task and mental load. In this experiment, the number of eye movements was counted for the experienced and less-skilled pilot. According to this result, a strong relationship was found between task and operator working behaviours like during taxi, take-off, and landing (experienced and less-skilled pilots) seen in Figure 48.

![Comparison of eye movement between experienced and less-skilled pilots](image)

**Figure 48: Comparison of eye movement between experienced and less-skilled pilots**

(Source: Own Edition)

According to the eye movement results, I found that the less-skilled pilot makes more eye movements during taxi (35%), take-off (37%) and landing (41%) in comparison to experienced pilots (Figure 48). On the other hand, in case if the complexity of task increases, the number of eye movements per second also respectively increases.

In order to examine the number of eye movement and eye blink rate during different flight tasks, three flight scenarios\(^1\) were designed: (i) Visual Meteorological Conditions (VMC), (ii) Instrument Meteorological Conditions (IMC), and (iii) IMC with ADI (Attitude Directional Indicator) failure (Figure 49).

\(^1\) The description of the flight scenarios will be given in the Chapter 3.3
According to the results, the number of eye movement of experienced pilot was found (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 (Figure 49).

In this research, eye blink rate was used as a measure of studying the connection between the mental state and the complexity of flight tasks. The human eye blinks once every four or five seconds on average – that is approximately 15-20 times per minute [165]. Eyeblink rates can be affected by a variety of different factors such as human behaviours, experience level, task (nature, difficulty, and engagement) and endogenous state (mental activity, psychological state, and state of attention). Several studies have shown that an increased level of task difficulty results in less frequent eye blinking [157]; [158]; [159]. According to Jyotsna and Amudha [157], a constant increase in the level of task difficulty will increase the cognitive load and which results in a reduced number of eye blinks. In contrast to these researchers, some other studies reported that the blink rate is increasing as the task difficulty increased; [160]; [161]; [162]. Tanaka & Yamaoka studied the relationship between blink rate and task difficulty and reported the more difficult the task became, the higher was the blink rate [160]. Additionally, a limited number of studies found no relationship between the degree of task difficulty and the blink rate. For example, Pauline Cho [163] reported that the level of task difficulty did not affect the blink rate in primary gaze and downward gaze. In this research, the eye blink rate of an experienced pilot was investigated through three flight scenarios².

² The description of the flight scenarios will be given in the Chapter 3.3
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 (Figure 50). In addition to this, it is also noticed that eye flutters (rapid muscle movement in the eyebrow area) also increased.

According to the outcomes of these experiments, the direct relationships were found between task difficulty and both eye movement and eye blink rate. As discussed earlier, a number of studies support the outcomes and methodology of the experiments. On the other hand, some others against these results. However, in my newly built concept, the autonomous system recognizes the operator in the loop and after start to continuously measure and store all the parameters on the subject in the operator environment including eye movement, blink rate, skin resistivity, and heart rate, etc. The autonomous system will have the ability to know what is the normal or abnormal value for each of the vital health parameters for a specific subject from the continuously stored data. In the case, if the system detects any sharp changes in the operator’ vital health parameter(s), the autonomous system will automatically be reported to the control managers and supervisors, and generate some suggestions to the operators.
3.3 Developing the measuring subsystems

**Eye-tracking:** Eye movement is a necessary component of the visual analysing of a human being. Eye movements reflect human emotions, stress and cannot be hidden, unlike other emotional demonstrations such as hand movements or voice changes. This specialty, therefore, lets researchers observe eye movement-related to many scientific studies, including psychology, human behaviour, cognitive science, marketing, and applied research fields. The eye movement from one fixation to the next is called a saccade. This can be measured in terms of radial degrees. There is a different component of saccades such as visual angle (the length of the saccade), the speed of the saccade in degrees per second, and the direction of the saccade. On average, humans make 2–3 saccades a second [166]. The eye-tracking technology was used to track the eye movements by recording fixations and saccades within the time of the test. The eye-tracker records and saves the information that can be presented with a heat map, cluster and gaze plots. Eye movements provide numerous clues to underlying cognitive processes operators encode information, and what information they use or ignore related to their performance under flight scenarios. In this research, TOBII eye-tracker has been used to record the visual patterns of the pilots through failure scenarios, such as engine failure and equipment failure of the Department of VRHT at BME. This research has been carried in collaboration with the Department of Ergonomics and Psychology in the flight simulator of VRHT at BME. The first calibration has been done according to the pilot’s eye movements.

![Figure 51: TOBII Eye-Tracker calibration (left) and usage in the flight simulator (right) (Source: Own Edition [13]; [14]; [50])](image)

Figure 51 shows the pilot’s eye movement during the engine failure scenario. Several areas of interest in the cockpit were defined to study gaze allocation during the simulated scenario. According to the result, after the engine failure, the pilot spent most of his time gazing at the engine instruments and finding the best place to make a precautionary landing somewhere off of the airport.
The radius represents the lengths of the fixations, so larger the dots, more prolonged fixation is. The heat maps show the prominent locations and area of interest. From this visualisation, eye-tracking data can be stored, and some quantitative statistics can be made, thereby operator behaviour in a flight simulator can be coded. On the other hand, utilising the eye-tracking glasses can be introduced into the pilots’ learning and training processes. Especially this device would be useful in the learning process of student operators or less-skilled operators. For example, flight instructors can help student pilots to learn more quickly, manage time spend on each instrument and adopting more rapidly to make particular processes, as landing and take-off.

**Binoculars:** First, a special system was developed by the use of the binocular box. After, four motion cameras were built into the flight simulator laboratory of the VRHT test environment (simulating the remote/virtual control tower), and the position of the binocular box was detected. By use of the defined position of the box, the target was determined (Figure 53). Finally, near the target, a new window was open on the screen, and the available information about the target was shown. To validate the concept of application of the motion tracking system, a test set up was built in the simulator laboratory of the Department (Figure 53). The motion tracking cameras were placed above the test area to ensure the unobstructed view on the target. In the test area, a binocular was placed, which was followed by the motion tracking system. The system tracked the motion of the binocular and from the position and orientation a self-developed algorithm determined the point of gaze. An information providing system was also developed to test the applicability of augmented reality and to develop methods load and information management methods to this concept.
The planned use of the eye-tracking system for supporting pilots’ work will be integrated into the load management supporting system, but it will deliver information about objects that ATCO’s look at. Therefore, it will be associated with information support systems, and with the monitoring, detecting and decision support systems as well. The test results were showed that the developed test system is accurate enough to support the work of controllers in a classical tower and a more modern remote tower environment in the future. The HungaroControl presented the test system based on the developed concept in the world ATM Congress (Figure 54).

**Heart Rate Measurement:** In this study, the heart rate of the pilots was recorded through three flight scenarios with a heart rate monitor system by a flight simulator is examined. The purpose of this study reported in this thesis was to show how pilots’ heart rate is affected by various flight factors through simulated scenarios. This experiment would provide a better
understanding of the relationship between a total load of operators and task complexity. In order to examine this, three flight scenarios were created: (i) Visual Meteorological Conditions (VMC), (ii) Instrument Meteorological Conditions (IMC) and (iii) IMC with ADI (Attitude Directional Indicator) failure.

**Task Protocol**

You are lined up and holding short at RWY25L. Configure the aircraft for take-off (trim +5, flaps takeoff, fuel pumps on, landing light on) and check the instruments.

**Takeoff from RWY 25L**
- Set power for take-off (Manifold pressure 40)
- Airspeed (blue line speed)
- 300feet AGL gear up flaps up, set climb power (manifold pressure 39, RPM 2600), fuel pumps off, landing lights off
- Maintain runway heading (250°) until reach 1000 feet MSL
- Climbing right turn to head 340°
- Stop climbing at 2500 feet and turn right to heading 070° for downwind.

**Fly straight on downwind**
- Maintain 2500 feet.
- Configure the aircraft for the cruise (Manifold pressure 22, RPM 2400)

**Approach and land on RWY25L**
- Reduce power for approach (RPM forward, throttle pull back as required), fuel pump on, landing lights on
- Turn right to HDG 160
- Set approach flaps and gear down when airspeed is in the white arc.
- Approach speed: blue line speed
- Land on RWY 25L.
- Stop on the runway.

**Scenario 1: Visual Meteorological Conditions (VMC):** VMC is the meteorological conditions in which visual weather minimums apply to flights conducted under Visual Flight Rules (VFR). These meteorological conditions expressed in terms of visibility, distance from clouds, and ceilings are equal to or higher than minimum VFR requirements. Moreover, solely pilot has the responsibility of visual traffic separation from terrain and other aircraft during VFR operations. In the first scenario, all pilots performed a visual approach procedure in a full flight simulator while their heartbeats were recorded with a heart rate monitor (Figure 55). This task requires significantly less pilot effort, which induces fewer operator loads. Because pilots have strong visual references with the horizon which means they are able to see in front of and
around their aircraft while in the air, (Average Heart Rate: 82,4 bpm- Standard Deviations (SD): 10,8- Root Mean Square (RMS): 83,1).

**Scenario 2: Instrument Meteorological Conditions (IMC):** IMC is the meteorological conditions in which expressed in terms of visibility, distance from clouds, and ceiling less than minima specified for Visual Meteorological Conditions (VMC). IMC requires pilots to navigate aircraft solely by reference to flight instruments, and therefore under instrument flight rules (IFR), rather than by outside visual references under Visual Flight Rules (VFR). Typically, this means flying in cloudy or severe weather. In the second scenario, all pilots performed an instrumental approach procedure with poor visibility from start to landing. This scenario was created significantly higher workload and accordingly stress, resulting in the increase in pilots’ heart rates, (Average Heart Rate: 96,8 bpm- Standard Deviation: 6,95- RMS: 97,0) shown in Figure 55.

**Scenario 3: IMC with ADI (Attitude Directional Indicator) failure:** ADI also known as the artificial horizon is the main instrument used to inform the pilot of the position of the aircraft in relation to the surface of the earth. It depicts whether wings are level or bank, if the aircraft is climbing or descending, or flying straight and level. In instrument flight, the pilot navigates only by reference to the instruments in the aircraft cockpit. If an aircraft has a failure of the attitude directional indicator while flying by instruments in IMC, pilots should concentrate primarily on the turn coordinator. And also a pilot in command should be continuity checked the Horizontal Situation Indicator (HIS), the Vertical Speed Indicator (VSI) and the Airspeed Indicator (ASI). A proper interpretation of these flight instruments will be given mostly the same information as there is no aircraft failure, but this emergency situation requires higher pilot effort and workload. The third scenario is the most stressful operations a pilot can carry out. In simulator sessions, pilots being monitored showed the most significant heart rate increase (Figure 55; Figure 56) during this scenario (Average Heart Rate: 103,9 bpm- Standard Deviation: 6,98- RMS: 104,1).
The heart rate of the pilot significantly increases under instrument flight rules – IFR (Task 2) and IMC failure. As seen in Figure 56 that in the case of the first scenario, the average of the heart rate (82.4 BPM) and the amplitude have the smallest value where the Standard Deviation
(SD:10.8) has the highest value compare to the second and third scenarios. Based on these 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. Most aviation accidents are attributed to human errors under these conditions.

**Electrodermal Activity Device (EDA):** The activity of sweat glands causes skin conductance and sweating causes a brief drop in the electrical resistance of the skin. This resistance also can be measured by means of electrodes placed on the operators’ wrist and shoulder. In collaboration with the Department of Affective Psychology at Eötvös Loránd University (ELTE), EDA measurement was realised in the flight simulator of the VRHT at BME. For the present study, the skin conductance activity of an experienced pilot was measured with Open Source Bio-Monitor (Obimon) for electrodermal activity in a flight simulator. Obimon is a small and reliable device capable of synchronised measurement that was used to record EDA from the wrists and shoulders of a pilot (Figure 57). It measures sweat gland activity by taking into account the “Skin Conductance Level” (SCL). For example, when operators are emotionally aroused, sweat gland increases and SCL are increases as well. Skin conductance is an indicator of sweat glands, so whenever the operator aroused, stressed or unbalanced loaded, sweat glands increase, and SCL gets higher respectively.

![Figure 57: Electrodermal activity device (EDA) usage in the flight simulator (Source: Own Edition: [16]; [14]; [50])](image)

The Skin Conductance Level of a pilot was recorded 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. Also, based on analyses of the measured EDA, the arousal was found to be high, when the flight took turns. This is an interesting finding that needs to be replicated in further studies.

3.4 Testing the developed monitoring system

**Stochastic process and Markov Chain**

Let us suppose that \((\pi, F, P)\) is a probability space, and \(X = \pi \to R\) is a random variable. Here \(\pi\) is a space, \(F\) is a \(\sigma\)-algebra of subsets of \(\pi\), \(P\) is a countably additive, non-negative measure on \((\pi, F)\) with total mass \(P(\pi) = 1\) and \(X\) is a measurable function. A stochastic process is simply a collection or ensemble of random variables and random functions indexed by a variable, usually representing \(t\) (time). This will be useful to consider the cases of discrete-time and continuous-time separately. According to a Discrete-Time Stochastic Process, \(X = \{X_n, n = 0,1,2,3 \ldots \}\) is a countable domain of random variables indexed by the non-negative integers. According to a Continuous-Time Stochastic Process, \(X = \{X_t, 0 \leq t < \infty\}\) is an uncountable domain of random variables indexed by the non-negative real numbers [167].
Figure 59: Mathematical representation of stochastic process [167]; [168]

\( \omega_i \rightarrow \text{Elementary Events} \)

\( \pi \rightarrow \text{Event Space} \)

\[
\forall \omega_i \in \pi \ (i = 1,2,3 \ldots n) \ldots 1
\]

\[
\omega_i \cap \omega_j = 0 \text{ if } i \neq j \ldots 2
\]

\[
\omega_1 \cup \omega_2 \cup \omega_3 \ldots \omega_n = \pi \ldots 3
\]

\[
\omega_1 = \varepsilon(t, \omega_1) = \varepsilon_1(t)
\]

\[
\omega_n = \varepsilon(t, \omega_n) = \varepsilon_n(t)
\]

Scientists face very often a situation where repeating the experiments under the same condition will give them a new realisation of signal or outcomes which are not quite the same as before. A Markov process is a general class of the random process indexed by time, and with the property that the future is independent of the past. A stochastic process has the Markov property if its future evaluation depends only on its current position, not on how it got that state. According to Prof Tsitsiklis ([167]; [168]), the basic idea of this situation can be explained as follows: “In physics, we write down an equation of how a system evolves that has
the general form. The new state of the system one second later is some function of the old state.

New state = f (old state) 3.6

For example, in the case of a particle movement, if a researcher knows the velocity and location of the particle then s/he can easily predict the exact location of the particle in some minutes later. However, in Markov Process has some randomness inside of the equation [169].

New state = f (old state, noise) 3.7

So, it describes the evaluation of the system in the presence of some noise, so that motion itself is a bit random.

\[
P_{ij} = P(X_{n+1} = j | X_n = i)
\]

\[
P(X_{n+1} = j | X_n = i, X_{n-1} ... X_0)
\]

This situation can be explained as follows: if a particle is at state \( i \), and what is the probability of being the same particle at state \( j \). First of all, the set of the possible states of a system should be written down. And then it is necessary to describe all the possible transitions between the states. For example, Aircraft arrivals and departures at an airport:

![Figure 60: An example of a Markov Chain](image)

At any given time, the following scenarios can possible happen:

(i) There would be an aircraft arrival which moves the state one higher,
(ii) There would be an aircraft departure which moves the state one lower,
(iii) There is also a possibility of nothing happen (no arrival and no departure) in which case state stays the same
(iv) There is also a possibility that an arrival and a departure at the same time in which case state again stays the same.

Let us assume that there are two aircraft at the airport, the probability of going one step down:

\[
PP_{21} = q(1 - p)
\]

98
This means that there will be only a departure and no arrival. Some of the other probabilities are the following:

\[ P_{23} = p(1 - q) \]  

\[ P_{22} = pq + (1 - p)(1 - q) \]  

\[ P_{00} = 1 - q \]  

\[ P_{01} = p \]  

In the case of heart rate measurement, there is only one process. The first step is to define the maximum and minimum value of operators’ heart rate signals. And then, the time between the max. and min. value can be divided into several discrete subspaces. This distance between the subspaces does not have to be same. In other words, if an interesting area or interval is found, the particular zone can be divided into more subspaces. One of the advantages of using the Markov chain method in operator heart rate measurement is, the state of signals can be seen clearly, and this would allow researchers to predict the future of signals. The repeating situations of operator heart rates can be defined by this method as well. Heart rate is randomly changing; therefore, the set of a possible state of the system should be written first and then and describe the transitions between the states as stated earlier.
In case of heart rate signals, let us assume that we are at the state $S_i$. There is a possibility that operator might face some difficulties and respectively their heart rate will be increased in which moves the state one higher, $S_{i+1}$. The second possibility is, the operator would get some relaxations in which moves the state one lower, $S_{i-1}$. And the last possibility is there is no change in the heart rate of operators in which case state stays the same, $S_i$.

**The stochastic load model of flight risk:** Accidents are a result of the situation process, which is assumed to be similar to the one given in Figure 63. Here $N$ stands for normal situation, $w_{\text{under}}$ is the warning systems for operator underload situation, $w_{\text{over}}$ is the warning systems for operator overload situation and $S_1$, $S_2$, $S_3$, $S_4$, $S_5$ and $S_6$ are different states related to the case when operator overloaded ($w_{\text{over}1}$, $w_{\text{over}2}$, $w_{\text{over}3}$ or under loaded ($w_{\text{under}1}$, $w_{\text{under}2}$, $w_{\text{under}3}$).

![Diagram of stochastic load model of flight risk](Source: Own Edition)
In this model, the parameters of overload and underload states were defined as follows:

- In the case of the operator overload situations: $w_{over1} = 0.8$ (warming signal must be generated), $w_{over2} = 0.9$ (calling the special attention on continuously monitoring the operating condition), and $w_{over3} = 0.95$ (immediate actions are required).

- In the case of the operator underload situations: $w_{under1} = 0.2$ (warming signal must be generated), $w_{under2} = 0.1$ (calling the special attention on continuously monitoring the operating condition), $w_{under3} = 0.05$ (immediate actions are required).

In addition to this, the “normal situation” is highly influenced on operator loads (work, task, information, communication and mental load) and as well as several other factors such as structure, surrounding, weather condition, traffic complexity, skill and tacit knowledge of operators, etc. For example, if there is a failure in an avionic system or the weather condition is too poor, operators tend to get more nervous than normal situation. The created model seen in Figure 63 can be calculated for each of the operator load separately. In this case, the operator load index calculation method was defined, by the current researcher, by the following formula:

$$i_{Load} = \sum_{i=1}^{5} w_{ei}(u, z)L_c$$  \hspace{1cm} 3.15

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.

$$i_{Load}[k + 1] = \sum_{q=1}^{r=9} (A[k]i_{Load}[k] + w_uB[k]u[i_{Load}[k]] + w_zF[k]z[k])$$  \hspace{1cm} 3.16

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).
In this concept, the autonomous system recognises the operators in the loop and case if the system detects any unbalanced loads (overload or underload situation), the system first generates some suggestions to the operators which will be shown on their screens, and sends alerts and warning messages to the managers and supervisors. If the operators in the loop are incapable of dealing with the routine tasks (such as strip marking, transferring an aircraft to the next sector) or failure, the control of aircraft will able to take over from the pilots in the loop by ground operators or the fatigue ATCOs can be replaced with the fresh ones.
Chapter 4

4 Developing the operators (Pilots, ATCOs)’ load management

4.1 Concept development – rules and methods

The operator load management concept was developed separately for overload and underload situations. As discussed earlier, there are five types of operator loads, i.e. work, task, information, communication and mental load. In the case of the overload situation, two different variations of load management methods can be used; (i) assign a scoring method - say in [0,1] to all the measurements and (ii) mathematical modelling. According to the assigned a scoring method, all the measurements should be transferred to scores on a 0 – 1 for each operator load (Table 3) where each element should have a weighting coefficient corresponding to different environmental conditions, abnormal situations and failures. Each case can generate a weighting coefficient between 0 to 1, and if there is more than one situation that plays a role at the same time, the total score will be the sum of all weighting coefficients.

Figure 64: Demonstration of the developed rectangular gauge on a 0 - 1 scale for overload situation management (Source: Own Edition [14]; [23])

According to the developed model in Figure 64, the score is 0 if there is a very normal task of load measurement, and it is 1 when an operator’s load may cause a severe accident. There will be five rectangular gauges, each of which displays a different level of operator load.
currently being experienced by an operator. According to the mathematical model, two different rules might be used for overload situation:

(i) If one of an operator’s load reaches the threshold where is the score,
- 0.8 – warming signal must be generated,
- 0.9 – calling the special attention on continuously monitoring the operating condition,
- 0.95 – immediate actions are required.

(ii) combination of at least two loads, namely in a case when any two types of load coefficients, reach to 0.7 or above (Figure 65):
- 0.7 – warning,
- 0.8 – monitoring,
- 0.9 – immediate action required

Figure 65: Combination of operator loads for overload situation management (Source: Own Edition [14]; [23])
The metrics and transformation of the measurements to the scores, and the definition of the warning levels, need further studies and might be defined depending on the operational condition and environment.

<table>
<thead>
<tr>
<th>Task Load</th>
<th>Basic Score</th>
<th>Weather Condition</th>
<th>Air Traffic Complexity</th>
<th>Operator Loads (over/underload)</th>
<th>Under being in abnormal/unforeseen situation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taxi</td>
<td>0.06</td>
<td>0.1 – 0.3</td>
<td>0.1 – 0.2</td>
<td>0.1 – 0.4</td>
<td>0.1 – 0.3</td>
</tr>
<tr>
<td>Take-off</td>
<td>0.12</td>
<td>0.1 – 0.3</td>
<td>0.1 – 0.2</td>
<td>0.1 – 0.4</td>
<td>0.1 – 0.3</td>
</tr>
<tr>
<td>Initial Climb</td>
<td>0.05</td>
<td>0.1 – 0.3</td>
<td>0.1 – 0.2</td>
<td>0.1 – 0.4</td>
<td>0.1 – 0.3</td>
</tr>
<tr>
<td>Climb (Flaps up)</td>
<td>0.09</td>
<td>0.1 – 0.3</td>
<td>0.1 – 0.2</td>
<td>0.1 – 0.4</td>
<td>0.1 – 0.3</td>
</tr>
<tr>
<td>Cruise/En-route</td>
<td>0.06</td>
<td>0.1 – 0.3</td>
<td>0.1 – 0.2</td>
<td>0.1 – 0.4</td>
<td>0.1 – 0.3</td>
</tr>
<tr>
<td>Decent</td>
<td>0.05</td>
<td>0.1 – 0.3</td>
<td>0.1 – 0.2</td>
<td>0.1 – 0.4</td>
<td>0.1 – 0.3</td>
</tr>
<tr>
<td>Initial Approach</td>
<td>0.05</td>
<td>0.1 – 0.3</td>
<td>0.1 – 0.2</td>
<td>0.1 – 0.4</td>
<td>0.1 – 0.3</td>
</tr>
<tr>
<td>Final Approach</td>
<td>0.08</td>
<td>0.1 – 0.3</td>
<td>0.1 – 0.2</td>
<td>0.1 – 0.4</td>
<td>0.1 – 0.3</td>
</tr>
<tr>
<td>Landing</td>
<td>0.46</td>
<td>0.1 – 0.3</td>
<td>0.1 – 0.2</td>
<td>0.1 – 0.4</td>
<td>0.1 – 0.3</td>
</tr>
<tr>
<td>Holding Pattern</td>
<td>0.20</td>
<td>0.1 – 0.3</td>
<td>0.1 – 0.2</td>
<td>0.1 – 0.4</td>
<td>0.1 – 0.3</td>
</tr>
<tr>
<td>Take a Turn</td>
<td>0.10</td>
<td>0.1 – 0.3</td>
<td>0.1 – 0.2</td>
<td>0.1 – 0.4</td>
<td>0.1 – 0.3</td>
</tr>
</tbody>
</table>

Table 3: Operator task loads with the weighting coefficients of the possible situations
(Source: Own Edition)

The management can be developed by the use of more sophisticated methods, like Markov's decision support. The control field of the cockpit can be designed with projecting the most necessary information (including loads, tasks, advice) in real-time mode to the cockpit window instead of having a series of wide screens in control panels. (Figure 65). It will help operators to manage their total loads more efficiently and reduce their stress levels at the same time. Another operator load management concept is an underload situation. As early sections indicate, technological developments have shifted the role of the operators from active control to passive monitor of the automated processes. Unbalanced operator load systems may accompany this highly automated system, unintended reductions in situation awareness, decrease in the quality of decision-making, and increased the level of stress. Sometimes the levels of operator loads become too low where the operator may become inattentive and/or bored. This happens because an operator's job sometimes can get monotonous. These situations generally referred to as operator underload, including work, task, information and mental underload. Operator underload caused attention to be withdrawn leading to the decrement. In order to manage operator underload, a management model was developed. According to the developed model in the score is 0 if there is a very normal task of load measurement, and it is 1 when an operator's load may cause a severe accident. There will be four rectangular gauges, each of which displays a different level of operator load currently.
being experienced by an operator. According to the mathematical model, two different rules might be used for underload situation:

(i) If one of the operator load drops to the threshold where is the score,

- 0.2 – warming signal must be generated,
- 0.1 – calling the special attention on continuously monitoring the operating condition,
- 0.05 – immediate actions are required

![Figure 66: Demonstration of the developed rectangular gauge on a 0 - 1 scale for underload situation management (Source: Own Edition)](image)

(ii) combination of at least two loads, namely in a case when any two types of load coefficients, drop to 0.3 or below:

- 0.3 – warning
- 0.2 – monitoring and
- 0.1 – immediate actions required

![Figure 67: Combination of operator loads for underload situation management (Source: Own Edition)](image)
4.2 Testing the load management system in a flight simulator and ATCOs’ laboratory

After having all the developed load monitoring devices, load management systems can be tested in a flight simulator and ATCO’s laboratory. All the load measuring systems can be built in an operator working environment and perform experiments through such scenarios for pilots and ATCOs, which lets researchers manage total operator loads [14]; [137]. While operators perform such scenarios, the level of their load systems can be tested with (i) displaying total load gauges and (ii) without showing them in order to understand what are the effects on operator loads. The result of the difference between these two situations will help researchers to understand better design the location of total load gauges in their environment as well. In case operators will be confused, stressed or aroused with continuously receiving their load information then operator total load gauges will be only displayed for the supervisor of operators who can make a decision on what to do. If the displayed total load gauges help operators to manage their tasks and increase their performance well, then these gauges can be displayed continuously in their environment. Regarding the operator load management system itself also can be tested whether the system works properly or not. This test can be done again through such flight scenarios. For example, in one scenario operator can be supported with only relevant information and the other scenario too much information can be provided to them in order to demonstrate the changes in the level of information load. Another possible scenario in order to measure information load can be a tunnel scenario, ATCOs can guide pilots with a variety of information and synthetic vision system that provides a 3D synthetic view to enable pilots to perform their tasks safely as seen in Figure 68. In this figure, red rectangular lights can be activated in front of the aircraft, which will navigate pilots through their route, particularly during take-off and landing phases of flight. Moreover, the second scenario pilots can be only received relevant information and not providing them with a synthetic vision system.
Depend on the level of the total load of ATCOs; the system gives some suggestions automatically directly to ATCOs or their supervisors. For example, respectively, to the level of ATCOs’ task, sector design and airspace configurations can be dynamically changed based on the level of the total load. This system helps to (i) balance the sector loads for ensuring safety, (ii) better use of availability of airspace, (iii) offer the maximum capacity to the incoming air traffic, (iv) best meet traffic demand at peak times operate with less staff, (v) reduction in fuel burn and emission, and (vi) minimising all costs. If the developed automated system detects an unbalanced load (overload/underload) of an ATCO, the supervisors may maintain the task of the ATCO according to the ATCO’s current capacity or replace him with a fresh one.

4.3 Concept verification and validation

The concept verification, validation and testing were continuously used during this research, and as well as model development simulation. Here are the major elements that are summarized. I was adopted and developed the new concept on operators’ load modelling, monitoring and management that could be used in simulation and testing in simplified forms as simulation and the testing element of the concept; therefore, we were verified and validated the concept only.

Concept verification means the evaluation of working the developed operator load models monitoring and management as intended. During the concept verification, the following aspects were studied:
I checked that the characteristics as heart rate, eye-movements, and skin resistivity, etc., and found that the results depend on mental conditions with real measurement data provided by cooperating partners.

By developed methodology, I was able to calculate the eye movement by using the motion camera in the operator working environment. The measurements were realized by parallel recording the voice of the operator, explaining what s/he is doing and where s/he is looking at and as well as motion camera recording. The results were shown that the area of interest could be detected by the motion camera data about 100% in case of the target size of more than 8 cm. If the distance between the elements is less than 8 cm or between the different elements is too small, then the accuracy is reducing radically to 50-60 %. In order to improve accuracy, the TOBII eye-tracker was used in the flight simulator [13].

The subjective decision of pilots was modelled by adaption of the methodology developed by Professor Kasyanov; the developed MATLAB simulation was tested by comparison of results of published by Professor Kasyanov and got in our software. According to the results of experimented pilots of middle size passenger aircraft, some differences were found by the current researcher in final decision-making. Not well-adjusted model parameters can explain this difference. However, the results according to the small aircraft were accepted by the experimented pilots taking part in the test in the flight simulator.

I discovered the new way of how to use the internet for concept verifications by inviting experts from around the world. A questionnaire was conducted to 212 operators (168 ATCOs (79.2%) and 44 pilots (20.8%)) in order to investigate the reasons for communication errors of operators (pilots, ATCOs) related to several factors such as cultural norms, regional accents, poor language skill, and social relations. The survey aims to find a way to avoid pragmatic failure in aviation communication [71].

Concept validation means the evaluation of the following of the developed operator load models, monitoring and management of the real processes. During the concept validation, the following aspects were studied:

- I had measurements in flight simulator certified and applying in pilot training and ATCOs’ environment simulation with generating the faults simulating the real processes.

- Before the measurement of operator vital health parameters (skin conductance, heart rate) during tests, I have measurements with the same pilots and instrumentation in control testing in a real environment for performing the predefined simplified tasks.
• Using the real data from validation exercise, which performed in the scope of the SESAR project, the data were used in testing the dynamic sectorization method. The conclusion was made applicability of dynamic sectorization by special large expert groups [39].
• A questionnaire was developed to investigate the reasons for misunderstandings between operators over the radio, which assessed cultural norms, social differences, and their effect on communication [71].

4.4 Discussion of the results

In this thesis, operator load monitoring systems were created in order to manage operator load in highly automated systems. First of all, the role of operators in future aviation systems as described, such as operators’ roles, working environments, and human factors. After Several well-known operator models were studied and adapted to the human operator work, such as “load model”, “situation awareness and decision-making model”, “subjective decision model”, and “information model”; thereby, a new operator load model was created and divided into five categories namely work, task, information, communication, and mental load. Then operator load measuring systems and monitoring sensors were created and integrated into the operators' working environment, such as eye-tracking, heart rate, and EDA skin conductance level sensors, etc. With the help of the developed systems, several test measurements were performed in the flight simulator of the VRHT at BME. The eye-tracking results highly suggest that utilising the eye-tracking glasses can be introduced into the operator learning and training processes. The eye-tracking device would be useful in the learning process of student operators or less-skilled operators. For example, flight instructors can help student pilots to learn more quickly, manage time spend on each instrument and adopting more rapidly to make particular processes, as landing and take-off. Based on the heart rate results, it can also be found that If the complexity of the task is increasing, the average of the heart rate is also significantly increasing. Most aviation accidents are attributed to human errors under an unbalanced operator load. This measurement lets the current researcher draw a mental picture of an operator in real-time. The results of EDA measurement were suggested that emotional arousal was highest during flight take off in comparison to en-route and landing in all the two conditions. Also, based on the analyses of the measured EDA, the arousal was found to be high, when the flight took turns. This measurement shows that the skin conductance level of operators can be measured continuously during their operation; the results let the current researcher monitor the mental load of operators. In this research, the subjective decision-making of the different levels of experience of pilots, namely (i) student pilot, (ii) less-skilled pilot, (iii) experienced pilot and (iv) well-experienced, were modelled during final approach on MATLAB 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. In other words, students and less-skilled pilots are not able to make their final decisions easily in which situations create chaotic orbits. The final decision time of the pilots can be calculated from these results by checking when s/he will not have any hesitancy between landing and go-around. Based on the results, this model is well usable for the investigation of the decision-making process of pilots from different skills and experience. This method will improve pilot training and help 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 levels of pilots while checking their way of thinking and decision-making process. Some unique aspects of operators were investigated in this thesis which influences safety like a 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. Lastly, operator load management systems were built by using the measurement. Two different variety of total load management methods were created 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.

With the developed system, operators will have tasks according to their current conditions including the level of total loads, state of physical and psychological parameters, and other aspects (traffic complexity, weather condition, unlawful actions, etc.). In this system, the vital health parameters of operators will be continuously measured and stored during operation. In this concept, the autonomous system recognises the operators in the loop and case if the system detects any unbalanced loads (overload or underload situation), the system first generates some suggestions to the operators which will be shown on their screens, and sends alerts and warning messages to the managers and supervisors. If the operators in the loop are incapable of dealing with the routine tasks (such as strip marking, transferring an aircraft to the next sector) or failure, the control of aircraft will able to take over from the pilots in the loop by ground operators or the fatigue ATCOs can be replaced with the fresh ones. The overall result of this thesis was suggested that the developed load monitoring and management methods serve as an excellent tool for balancing the total operator load; thereby, improving the performance of operators and increasing the safety of operators'
actions, particularly in an abnormal/emergency situation. Due to the consequent of this development in this research: (i) monitoring operator total loads, (ii) managing operator actions, (iii) increasing the level of situation awareness, (iv) reducing operator loads on subject, (v) better decision making and improving the quality of decision, (vi) Increasing operator effectiveness and productivity, and (vii) increasing safety particularly in abnormal/emergency situation. The outcomes of this thesis will be useful in balancing operator total load, creating operator training courses, designing operator working environments (cockpit and ATC systems), and decreasing communication errors between operators, etc.
Chapter 5

5 Conclusions

Due to rapid development in automated systems in aviation, it is expected that the role of operators will be changed from active controlling to passive monitoring. This highly automated system may be accompanied by unintended reductions in situation awareness, unbalanced operator load, increased stress, and issues of mistrust, boredom, and monotony. Nowadays, operators are an active element of the system, but in the near future, they will be transformed to be a passive element of the system due to the introduction of intensive automation. In the new system, operators will monitor the operation of automatic systems and will have active roles only in an abnormal/emergency situation. While the responsibility of the operator to fly safely remain unchanged, several new skills are required to control aircraft [171]. The future operator environment (cockpit and future ground control tower of pilots) needs to be redesigned by taking into account various psychological parameters, human factors, and total operator load systems. As the avionics system became more complex, evaluation of the performance of operators was required, such as situation awareness, decision-making, and operator load. Operators need viable constructs, principles and aviation systems to promote a better understanding of automation and balancing their loads in complex circumstances. In addition to this, the working conditions and operator loads require new management methods, and support systems as well. In this changing environment, the old operator model needs to be redefined; hence the concept of the future operator model was developed and introduced in this thesis. Management of mental and information load is going to have a more significant role in the new working environment, which requires a more advanced supporting system.

The present doctoral dissertation has the scope to develop general load monitoring and management systems working in highly automated systems. To do so, first, the role and load of operator were investigated and analysed by using (i) outside measurements (like motion camera, eye-tracking), (ii) microsensors integrated into working environment (for example computer mouse, side stick, skin resistance, skin temperature), (iii) connecting directly to the operators body (heart rate monitor, EDA- Electrodermal Activity Device (OBIMON), ECG, EEG, sensors integrated into operator clothes), and (iv) adapting simulation methods like using method of subjective analysis. Second, in order to measure operator load, some load monitoring sensors and methodologies were developed such as eye-tracking systems, integration of microsensors into operator environments like side stick, and computer mouse.
There is a raising need for conducting further research regarding eye movement patterns and mental workload in real-time flight operations. Third, some of the well-known operator models like load model by Endsley, situation awareness model by Rasmussen and subjective characters of decision-making by Kasyanov were studied and adapted to the human operator work, working in highly automated systems. The subjective decision-making of the different levels 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. Fourth, a new operator load model was created including work, task, information, communication and mental load that was tested and verified in flight simulators and partly validated in real situations. In addition to this, in order to investigate some special aspects that influence safety like misunderstanding of communication, 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. Finally, the total load management rules were built and management methods were developed based on workload, task load, information, communication, and mental load for overload and underload situations. The conclusion in this thesis is elaborated into four groups: (i) description of the content, (ii) major results, (iii) thesis, and (iv) future plans/works.

5.1 Description of 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 as described, such as operators’ roles, working environments, human factors, and model. In the scope of the SESAR project, the real data from validation exercise were used in testing the dynamic sectorization method. According to the results, the dynamic sectorization and air space configuration may eliminate the task overload and reduce the actual load by 30-40 per cent [39]. 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”[172], Rasmussen “situation awareness and decision-making model”[100], Kasyanov “subjective decision model”[93], and Wickens “information model”[99]. 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 [13]. The created generalised model was used in developing the ATCOs environment [27]; [15]; [114] and less skilled pilot support [27]; [25]; [114]. The subjective decision-making of the different levels 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. During the final approach hesitation frequency and decision-making time were calculated for landing and go-around situations. The result of the research suggested that this method improves pilot training and helps instructors to understand the weaknesses of pilots better as well. In addition to this, some unique aspects of operators were investigated in this thesis which influences safety like a 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 [71]. In the third chapter, the load monitoring systems was developed and the measurements were performed such (i) Eye-tracking: Eye movement and area of interest of pilots (experienced and less-skilled pilots) were defined through several flight scenarios [114]. Eye movements are very depending on the task, experience, and human behaviours. Based on the eye-tracking measurement, a recommendation of using eye-tracking systems was developed for pilot training in the flight simulator [13]; [50]; [171]. (ii) Integrated microsensors and motion cameras: Microsensors [13]; [137] and motion cameras [16]; [13]; [26]; were used for developing the operators’ working environment to measure total load systems, thereby increasing the level of situation awareness and decision-making. A side-stick and a computer mouse with integrated sensors were built to measure pilots’ physiological conditions during flight tests such as skin resistance, skin temperature, and heart rate sensors. In addition to this, two motion cameras were installed in flight simulator of the department of VRHT at BME [13]; [137]. The eye movement, visual attention and eye blink of pilots (experienced and less-skilled) were measured in the flight simulation during take-off and final approach. In case if the complexity of task increases, the number of eye movement, and eye blink respectively increases. (iii) Heart rate measurement: The heart rate of pilots were measured in the flight simulator through three flight scenarios. A strong relationship was found between the complexity of the task and heart rate. 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 [13]; [50]; [114], and (iv) EDA (Electrodermal Activity) device: The Skin Conductance Level (SCL) of a pilot was recorded during all phases of the flight through a poor visibility and instrument failure flight scenario. Based on the analyses of the measured EDA, the emotional arousal of the pilot was found to be highest during flight take off in comparison to en-route and landing. In addition to this, the arousal was found to be high, when the flight took turns [16]; [14]; [50]. 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 [14]; [23]. Finally, the summary, major results, theses, and recommendations for the future works were presented.

5.2 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”, Rasmussen “situation awareness and decision-making model”, Kasyanov “subjective decision model”, Wickens “information model” and James Reason “Swiss cheese model”. 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. The created generalised model was used in developing the ATCOs environment (Figure 39; Figure 40, [14]; [15]; [27]) and less skilled pilot support (Figure 37; Figure 38, [14]; [27]; [50]).

- The research was made 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 [13]; [137]. By analysing the test results, the applied methodology showed that the developed system can be applied in the pilot training, ATCOs’ working environment, and as well as car drivers’ environment [24].

- Eye movement and the area of interest of pilots (experienced and less-skilled pilots) were defined through three flight scenarios. By analysing the result of operator eye-movements, eye-tracking systems can be a useful tool for pilot and ATCO training.

- A strong relation found between task and operator working behaviours like during taxi, take-off, and landing (experienced and less-skilled pilots). Eye movements are very depending on the task, experience, and human behaviours. 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.

- The complexity of the task is directly proportional to the number of eye movements per second. In other words, if the complexity of task increases, the number of eye movement per second also respectively increase. 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.

- 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. In addition to this, it is also noticed that eye flutters (rapid muscle movement in the eyebrow area) also increased.

- Eye-tracking and eye movement measurements were supported by measurements and applied load monitoring on the screen of pilots and ATCOs. In addition to this, a functional model of the pilot decision support system was created separately for pilots (Figure 37; Figure 38) and ATCOs (Figure 39; Figure 40).

- The subjective decision-making of the different levels 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 will improve pilot training and help 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 levels of pilots while checking their way of thinking and decision-making process.

- 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 [13; [50; [114].

- The Skin Conductance Level (SCL) of a pilot was recorded by OBIMON devices (an Electrodermal activity 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 all the two conditions. Furthermore, based on analyses of the measured EDA, the arousal was found to be high, when the flight took turns. Based on some of these parameters, 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 Figure 58, [16; [14; [50])

- I was taken part in a SESAR project dealing with airspace design and dynamic sectorization on the evaluation of the verification and validation results. I was detected that the task load, as defined by NASA - TLX, can be managed by defined by 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 [39].

- With the rapid technological changes, in many cases, information, communication, and mental load became potential problems that required aviation systems to monitor and control. Therefore, these load systems were separately defined and included in the Endsley load model (Figure 23, [15; [101]).

- Operator load index calculation method as defined by the current researcher, by the following formula:

\[ i_{Load} = \sum_{i=1}^{5} w_e_i(u, z) L_c \]  \hspace{1cm} (5.1)

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

\[ i_{Load}[k + 1] = \sum_{q=1}^{9} (A[k]i_{Load}[k] + w_qu B[k]u[i_{Load}[k]] + w_qz F[k]z[k]) \]  \hspace{1cm} (5.2)

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 conditions).
• Total decision-making time of operators was calculated by the following formula:

\[ t^{req} = t^{req}_{ue}(\sigma_k) + t^{req}_{dec}(S_a) + t^{req}_{react}(\sigma_k, S_a) \]

An operator must have time \( t^{req}_{ue}(\sigma_k) \) to understand and evaluate the given \( \sigma_k \) situation, making-decision \( t^{req}_{dec}(S_a) \) that intends to transit the situation process from \( S_k \) state into the \( S_a \) and the required time to perform the action \( t^{req}_{react}(\sigma_k, S_a) \).

• I found that (Figure 33; Figure 34) in a highly automated system, large mental load such communication overload loads are increasing. According to the investigation, I have recommended to include the English conversation using by different cultural norms and social relations in the pilot and ATCO training.

• In-flight simulator practice, the developed load monitoring, and management system serve as an excellent tool for improving the quality of operator training. According to the results, the load monitoring and management system increase the safety of operators’ activities, especially in an emergency situation.

## 5.3 Thesis

**Statement 1:** 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 systems\(^3\), including investigation of the operator situation awareness – analysis – decision-making process by using (i) outside measurements (like motion camera (Figure 45; Figure 53, [U.K.1]; [U.K.2]; [U.K.8]; [U.K.11]), and eye-tracking (Figure 35; Figure 51, [U.K.1]; [U.K.2]; [U.K.3]; [U.K.10]; [U.K.17]), (ii) microsensors integrated into operators’ working environment, like skin resistance, heart rate, and skin temperature sensors integrated into computer mouse, and side stick (Figure 41; Figure 43, [U.K.1]; [U.K.2]; [U.K.6]), (iii) connecting directly to the operators body: heart rate monitor/heart rate variability (Figure 55; Figure 56, [U.K.1]; [U.K.2]; [U.K.3]; [U.K.17]), ECG, EEG, EMG, EDA-Electrodermal Activity (Figure 57; Figure 58, [U.K.1]; [U.K.3]; [U.K.10]; [U.K.11]; [U.K.17]), sensors integrated into operator clothes [U.K.22], and (iv) adapting simulation methods like using method of subjective analysis (Figure 20; Figure 21).

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\(^3\) 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.
Thesis 1:
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 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 increasing the reaction time and frequency and amplitude of "hesitation" ⁴ (Figure 20; Figure 22; Figure 43, [U.K.1]; [U.K.2]).

Statement 2: 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, Figure 41). Based on the eye-tracking measurement, I have developed a recommendation for using eye-tracking systems for pilot training in the flight simulator (Figure 45; Figure 47; Figure 52, [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) failure (Figure 48; Figure 49, [U.K.2]; [U.K.6]).

Thesis 2: 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].

⁴ During final approach pilots are in a dilemma between landing and go-around.
I have defined how to interpret operator measured heart rate depending on the situations (flight scenarios and traffic situation). I found a strong relationship between the complexity of the task and heart rate (Figure 55; Figure 56, [U.K.2]; [U.K.10]; [U.K.13]).

I found that EDA measurements fully support the operator load index classification (Figure 57; Figure 58, [U.K.1]; [U.K.7]; [U.K.8]; [U.K.17]).

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 56, [U.K.7]; [U.K.8]; [U.K.13]).

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 35; Figure 36, [U.K.1]; [U.K.6]; [U.K.7]; [U.K.10]) and ATCOs (Figure 37; Figure 38, [U.K.1]; [U.K.6]; [U.K.10]; [U.K.23]).


Thesis 3: I have improved and adopted Endsley and Rasmussen 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” (Figure 17) into the created generalised model (Figure 15, [U.K.2]; [U.K.6]; [U.K.7]).
- I have included human behaviours (skill, competency, knowledge, tacit knowledge) into the created generalised model (Figure 15, [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 (Figure 37; Figure 39, [U.K.1]; [U.K.2]; [U.K.13]; [U.K.22]).

Statement 4: 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 tasks 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 in 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 4:** 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) (Figure 23; Figure 39, [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 (Figure 56, [U.K.10]; [U.K.22]).
- I made a recommendation to include the English conversation using different cultural norms and social relations into the pilot and ATCO training [U.K.5]; [U.K.9].

**Statement 5:** I investigated the possible operator (Pilots and ATCOs) load management methods for overload and underload situations.

**Thesis 5:** I was 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 attention (continuously monitoring the operating condition), and immediate actions required, respectively 0.8, 0.9 and 0.95 (according to the defined scoring method) (Figure 64, [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 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) (Figure 65, [U.K.1]; [U.K.10]; [U.K.14]).

- I defined thresholds for each load independently for underload situation as warning signals, calling special attention (continuously monitoring the operating condition), and immediate actions required, respectively 0.2, 0.1 and 0.05 (according to the defined scoring method) (Figure 66, [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) (Figure 67, [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 $u[i_{Load}[k]]$ 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 conditions) [U.K.1].

5.4 Future works and perspectives

In this thesis, the role of the pilots and ATCOs working in highly automated systems were investigated and general load monitoring and management systems were developed for operators. Several operator models were studied and adapted to the human operator including “operator load model”, “situation awareness and decision-making model”, “information model”, “subjective decision model”, “Swiss cheese model”, as a result, a new operator load model was created including five types of loads. Several load monitoring
sensors and methodology for monitoring of human operator loads (developed eye-tracking systems, integration of microsensors into operator environment like side stick, computer mouse) were developed and test measurements were performed in the flight simulator of the VRHT at BME through realistic flight scenarios. And finally, load management methods were created based on total load systems for overload and underload situations.

In this thesis, such applications like microsensor, eye-tracking device, heart rate monitor, electrodermal activity (EDA) device, motion cameras and outside measuring equipment were used in the flight simulator and ATC/ATM simulation laboratory of the Department of Aeronautics, Naval Architecture and Railway Vehicles (VRHT) at Budapest University of Technology and Economics (BME). However, further possible adaptation, series of tests, and experiments have been left for the future due to lack of budget and time. In my future work, I plan to make all those measurements with more number of pilots and ATCOs in flight and ATM simulators, and as well as in the real working environments. When I complete a wide variety of measurements, I will work on the ways of implementing the developed load monitoring and management equipment in pilots and ATCOs’ real work environments. Future work concerns system integrations into operator real working environment in order to build a continuous load monitoring and management systems.

During the consultation with universities and institutions, companies might have the interest of application of my methodology and results; therefore, we identified the following possible future areas:

- TOBI eye-tracking measurements in collaboration with the Department of Ergonomics and Psychology at Budapest University of Technology and Economics – Some measurements have been already performed in the flight simulator of the department of VRHT at BME.
- Electrodermal activity measurements (EDA) in collaboration with the Department of Affective Psychology at Eötvös Loránd University – Some measurements have been already performed in the flight simulator of the department of VRHT at BME.
- Pragmatic failure study in aviation communication in collaboration with the Corvinus University of Budapest – A yearlong study had been already made in 2018.
- Heart rate variability measurement in collaboration with the Heart and Vascular Centre at Semmelweis University – Several technical meetings have been already organised, and the heart rate variability measurement will be performed soon.
Own References


Bibliography


