Recommendations for augmenting the Human Performance Envelope

Ricardo Reis (EMBRAER), Daniele Ruscio (DBL), Nicolas Maille (ONERA), Carsten Schmidt-Moll (DLH), Matthias Wies (DLR)

Short abstract: Future Sky Safety is a Joint Research Programme (JRP) on Safety, initiated by EREA, the association of European Research Establishments in Aeronautics. The Programme contains two streams of activities: 1) coordination of the safety research programmes of the EREA institutes and 2) collaborative research projects on European safety priorities.

This deliverable is produced by the Project P6 “Human Performance Envelope (HPE)”. The objectives of this study are to review the HPE concept, to evaluate its benefits and to provide recommendations for future recovery methods and principles.

Programme Manager	Michel Piers, NLR
Operations Manager	Lennaert Speijker, NLR
Project Manager (P6)	Matthias Wies, DLR
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Contributing partners

Company	Name
EMBRAER	Ricardo Reis
DBL	Daniele Ruscio
ONERA	Nicolas Maille
DLH	Carsten Schmidt-Moll
DLR	Matthias Wies

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Matthias Wies	DLR	Main Author	14-06-2019
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Alex Rutten	NLR	Quality Assurance	25-06-2019
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Matthias Wies	DLR	Project Manager (P6)	14-06-2019
Lennaert Speijker	NLR	Operations Manager	25-06-2019

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ACRONYMS

Acronym	Definition
AC	Alternating Current
ACARE	Advisory Council for Aeronautics Research in Europe
ATM	Air Traffic Management
CAT	Category
CBT	Competency Based Training
EASp	European Aviation Safety plan
ECAM	Electronic Centralized Aircraft Monitoring
EFB	Electronic Flight Bag
ELEC	Electric
EREA	Association of European Research Establishments in Aeronautics
FDM	Flight Data Monitoring
HF	Human Factors
HMI	Human-Machine-Interface
HP	Human Performance
HPE	Human Performance Envelope
IATA	International Air Transport Association
ILS	Instrument Landing System
NASA	National Aeronautics and Space Agency
OEM	Original Equipment Manufacturer
RWY	Runway
SD	Status Display
SRIA	Strategic Research and Innovation Agenda
VFR	Visual Flight Rules

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EXECUTIVE SUMMARY

Problem area

Future Sky Safety (FSS) P6 addresses the building of ultra-resilient systems and operators, focussed on strengthening the resilience to deal with current and new risks of the humans and the organizations operating the air transport system. This builds on a concept previously proposed in the air traffic management domain, extending it to the human operators in the cockpit. The aim of P6 is to define and apply the Human Performance Envelope for cockpit operations and design, and determining methods to recover crew's performance to the centre of the envelope, and consequently to augment this envelope.

The Human Performance Envelope (HPE) is to some extent a new paradigm in Human Factors. Rather than focusing on one or two individual factors for example situation awareness or fatigue, the HPE considers a range of common factors in accidents and maps how they work alone or in combination to lead to a performance decrement that could affect safety. The safe region on the envelope is defined by human performance concepts, which can be signalled and measured, allowing the pilots to detect and recover, or enabling external agencies to prompt recovery, or allowing automation to kick in and take over.

Description of Work

This deliverable provides a review of the conducted work and results of the project and augments the gained insights about the Human Performance Envelope (HPE) concept. Furthermore, the deliverable gives recommendations for the use and application of the HPE. This work bases on the results of two workshops dealing with the review and augmentation of the HPE (Bordeaux May 2018 and Deep Blue May 2019), on the discussion during several project meetings, and on the results and experience gained throughout the project.

The HPE concept considers the individual effect of nine factors and the interaction effect of these factors on performance. At the beginning of the project, sensors were selected to measure the different factors and tested in preliminary experiments. They were validated in simulator experiments conducted in a full flight simulator with airline pilots. Some of the selected sensors turned out to be very suitable to assess the levels of the factors. Particularly, physiological sensors measuring i.a. heart rate and heart rate variability were sensitive with respect to changes in workload and stress.

Results & Conclusions

Overall, the HPE concept turned out to be a valid concept to assess the constraints that act on the pilots and that influence performance. Nevertheless, for complexity reasons the project investigated only three factors. Ideally, the effects and interactions of all factors should be investigated in the future. It should be noted that the factors should be selected according to their relevance given a specific scenario. In this project two different scenarios were investigated in which workload, stress and situation awareness were the prevalent factors. Therefore, these factors were selected. Furthermore, it should be noted that the investigation of the factors and their interaction should be done in experiments and scenarios allowing a

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controlled variation of the factors. In the project this has been achieved using two different scenarios. The first one was very controlled while the second one was more complex and realistic. This approach proved to be very beneficial to investigate both, the effects of the factors and the performance and difficulties pilots have in a complex realistic situation.

Currently, there is one main limitation of the HPE concept. Given the experiments conducted, it was difficult to predict the performance of pilots. This may be due to two reasons. First, only three instead of nine factors were investigated probably disregarding certain effects and interactions of the other factors. And second, the correlation of the variation of the factors and the variation of the performance is not linear necessarily. Further experiments are needed to investigate this relationship in more detail.

Applicability

There are two main areas of application of the HPE concept. First, it is very useful for Pilot Monitoring System (PMS). Concepts like reduced crew or single pilot operations are dependent on a reliable PMS. PMS again rely on the precise monitoring of the pilot condition. The HPE concept considers all relevant factors that need to be measured and monitored to determine the precise pilot condition. Using the identified sensors to measure the different factors of the HPE together with the results and insights of the project can enable the development of such PMS. The smart-vest developed within the project measuring physiological data is one good sensor that can be used for PMS. However, it should be noted that the level of each HPE factor should be measured with more than one sensor in order to increase the reliability of the overall system.

Second, the HPE concept is very useful to analyse problems pilots have in critical situations and to validate and certify new technologies, like new Human Machine Interfaces (HMI). Determining the performance of the pilots with the help of the HPE concept provides valuable information about those critical situations and the problems pilots have. Additionally, those data can be used to compare different design concepts with each and to evaluate their effectiveness. This highly supports the validation and certification process. Within this process it is important to previously define a desired pilot performance and behaviour. Following this definition, the relevant HPE factors need to be selected together with their sensors. The definition of the desired performance is important in order to correctly assess the actual performance measurement with the help of the HPE concept. Additionally, the comparison of the desired and actual performance will allow the definition of the boundaries (limits) of the HPE. If those steps are applied, the HPE concept can provide sound and valuable data that help to identify problems and to evaluate new designs and automation concepts. This highly facilitates the validation and certification process of new cockpit technology.

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1 INTRODUCTION

1.1. The Programme

The European Council Flightpath 2050 vision aims to achieve the highest levels of safety to ensure that passengers and freight as well as the air transport system and its infrastructure are protected. Trends in safety performance over the last decade indicate that the Advisory Council for Aeronautics Research in Europe (ACARE) Vision 2020 safety goal of an 80% reduction of the accident rate is not being achieved. A stronger focus on safety is required.

Future Sky Safety, established under coordination of EREA (Association of European Research Establishments in Aeronautics), is a transport research programme built on European safety priorities that brings together thirty-three European partners to develop new tools and new approaches to aviation safety. The programme links the EASp (European Aviation Safety plan) main pillars (operational issues, systemic issues, human performance and emerging issues) to the Flightpath 2050 safety challenges through four themes:

- **Theme 1** (new solutions for today's accidents) aims for breakthrough research to address the current main accident categories in commercial air transport with the purpose of enabling a direct, specific, significant risk reduction in the medium term.
- **Theme 2** (strengthening the capability to manage risk) conducts research on processes and technologies to enable the aviation system actors to achieve near-total control over the safety risk in the air transport system.
- **Theme 3** (building ultra-resilient systems, organizations and operators) conducts research on the improvement of systems, organisations and the human operator with the specific aim to improve safety performance under unanticipated circumstances.
- **Theme 4** (building ultra-resilient vehicles) aims at reducing the effect of external hazards on vehicle integrity as well as reducing the number of fatalities in case of accidents.

Together, these themes and the institutionally funded safety research intend to cover the safety priorities of Flight Path 2050 as well as the ACARE Strategic Research and Innovation Agenda (SRIA) (in particular the challenges brought forward by ACARE Working Group 4 "Safety and Security"). The programme will also help coordinate the research and innovation agendas of several countries and institutions.

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1.2. Project context

Future Sky Safety P6 addresses theme 3 (building ultra-resilient systems and operators) focussed on strengthening the resilience to deal with current and new risks of the humans and the organizations operating the air transport system.

P6 builds on a concept previously proposed in the air traffic management domain, extending it to the human operators in the cockpit. The aim of the project is to define and apply the Human Performance Envelope for cockpit operations and design, and determining methods to recover crew's performance to the centre of the envelope, and consequently to augment this envelope.

The HPE is to some extent a new paradigm in Human Factors. Rather than focusing on one or two individual factors for example situation awareness or fatigue, the HPE considers a range of common factors in accidents and maps how they work alone or in combination to lead to a performance decrement that could affect safety. The safe region on the envelope is defined by human performance concepts, which can be signalled and measured, allowing the pilots to detect and recover, or enabling external agencies to prompt recovery, or allowing automation to kick in and take over.

1.3. Research objectives

The project defined the Human Performance Envelope, conducted preliminary experiments in order to select and assess sensors for measuring the Human Performance Envelope, conducted first flight simulator experiments in order to validate the Human Performance Envelope and the sensors, developed new Human Machine Interfaces in order to recover the performance of the pilots, and finally conducted second flight simulator experiments in order to validate the new Human Machine Interfaces.

The objectives of this report are to review the concept of the Human Performance Envelope and to evaluate its benefits and to provide recommendations for future recovery methods and principles.

1.4. Structure of the document

Chapter 2 of the document consist of three subchapters. The first subchapter 2.1 deals with the measurement of the Human Performance Envelope. The second subchapter 2.2 discusses the application of the Human Performance Envelope for pilot monitoring systems and Human-Machine-Interface (HMI) design. The last subchapter 2.3 assesses the Human Performance Envelope in the context of a highly automated environment. Section contains the main conclusions and recommendations of this study.

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2 RECOMMENDATIONS FOR AUGMENTING THE HUMAN PERFORMANCE ENVELOPE

2.1. Measurement of the Human Performance Envelope

2.1.1. Human Performance Envelope measurements

The concept of Human Performance Envelope (HPE) aims to consider a full range of factors in order to map how they work alone or in combination to lead to a Human Performance (HP) modification. While several indicators, tests, metrics, and tools to measure individual Human Factor (e.g. mental workload, visual attention etc.), have been produced over the years, there is still a need to better assess how to offer precise ways to monitor the combination of multiple range of factors within a HPE framework. This consideration is especially relevant for complex Human Factors concepts like stress, fatigue and vigilance.

In aviation research these factors are not always represented by univocal metrics and are investigated by a series of behavioral indicators that mostly focus on cognitive concepts (disregarding the emotional aspects concerning perception and management) or by neurophysiological indexes that require additional analysis to better understand the combination of processes that they could reflect (e.g. autonomic nervous systems modulations).

To assess the HPE measurement, a series of experimental trials were set up in the course of the project. Different tasks designed to control and manipulate the levels of different human factors in a HPE framework and different configurations of the Human Machine Interfaces (HMI) were manipulated in order to provoke degradation of pilot performance and to measure the impact of HPE factors on pilots' performances (e.g. see deliverables D6.2 D6.3).

Among the different measures collected during the experiments, some of the measurements were particularly suitable to be standardized and grouped together to assess the modifications and combinations of several HPE factors. For Instance, for the step2 versus step 3 comparison (see D6.5 and 6.6), heart rate and fixation duration were integrated with the qualitative data collected from the pilots (benefits questionnaire and performance curve) using a mixed approach that provides a useful estimation of the HPE interactions.

For example, when considering the time spent by the pilots looking at the status display (SD) of the A320, it appeared that it was significantly affected by the different configurations of the HMI (standard versus new), but it was not clear if the longer fixation duration represented an increase of workload of the new HMI or rather the HMI that required longer visual attention process to extract information. The standardized integration with benefits questionnaire results showed the reasons why some elements of the SD actually supported the pilot performance (e.g. looking longer at the SD because the information there was helpful for the given task under that given circumstance) versus the elements of the SD that interfered the pilot performance during certain task (e.g. taking more time looking at the SD to obtain/supervise the required information). The combination of the qualitative and quantitative data

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contributed to achieve better insight on the overall pilot's performance and, thus, indirectly contributed further to the validation of the HPE measures.

The project deployed studies and simulation exercises that led to the specification of key measures that can track the pilot's state in real time. To achieve this, the development of a realistic scenario was accompanied by measuring the HF indicators with state-of-the-art technology.

As part of the project, a new 'smart-vest' was developed and used which wirelessly captures a range of electrophysiological measures. Furthermore, eye-tracking and pupil dilation measurement were uses as well as a series of structured user interviews (e.g. benefits questionnaire, cognitive walkthrough, and performance curves) to collect the qualitative data. Using this combination of measures provides a way to determine when more support from the aircraft systems might be needed during a complex, deteriorating situation.

2.1.2. Realism of the Human Performance Envelope experimental scenario

Two scenarios where developed to measure and validate the HPE and to validate the newly developed Human-Machine-Interfaces (HMI). Scenario 1 consisted of an ILS approach with manual control into the airports Frankfurt and Hannover. The levels of the difference HPE factors were varied in a total of 8 runs.

Scenario 2 consisted of an approach into the airport Bremen while the following events took place which increased the levels of the HPE factors to a maximum during the run:

- Approaching Bremen with standard fuel for 50 min remaining flight time
- Preparation of CAT1 approach RWY 27
- Go-around during ILS approach RWY 27 due to slow preceding (VFR) traffic
- During downwind ELEC AC BUS 1 Failure
- Constantly increasing workload due to the procedure and the time needed
- Decision making and handling of complexity under low fuel conditions
- CAT2 ILS approach RWY 09
- Possible engine flame-out due to amount of fuel

As scenario 2 formed the basis for the identification and validation of necessary HMI improvements, its realism is important. Therefore, the probability of the occurrences of the events will be discussed in the following. There are three different conditions in the scenario:

1. Condition: Amount of fuel

To arrive at the destination airport (in this case Bremen) with 65 min of remaining fuel. Having Hamburg as alternate with an alternate fuel (flight time) of only 18 min, that gives you an additional extra fuel of 17 min.

30 min final reserve + 18 min alternate fuel + 17 min extra fuel = 65 min upon arrival

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The point measuring those 65 min is in the base turn to final of RWY 27. That amount of fuel upon arrival is common and will be taken by about half of the pilots.

2. **Condition: Technical failure**

The technical failure of an AC BUS 1 FAILURE is a regular electrical failure which occurs at an average rate of 10e-5. There are other electrical failures which are less complex, but we chose this one because it needs some additional information which can only be obtained when using the electronic flight bag (EFB) which is situated next to every pilot.

3. **Condition: Slight weather change**

A slight wind change of 50 degrees and a minor decrease of visibility in the scenario are also common and may happen, even several times during the day. That is the most common occasion. Both values change to the disadvantage of the pilot.

In the following an estimation of the probability of the occurrences of the events will be given:

All three conditions combined occur with a probability of about 10e-5 for half of the flights (because half of the pilots will have that amount of extra fuel or even less fuel and the other half of pilots will have more fuel upon arrival). A rough estimate: there are 10 million flights in Europe, half of that is 5 million, divided by 100.000 (10e-5) is about 1 to 50 occurrences per year in Europe. Long and short haul combined. For a big airline it means 1 to 10 scenarios of this kind in its operation per year. And looking at the flight data monitoring (FDM) and maintenance numbers, it does fit with the database.

The question remains, why there are not more crashes with such a large amount of occurrences per year. With scenario 2 and the experimental setup there was one specialty: it tested only the co-pilot for reasons of reducing and controlling the empirical variance. The other pilot, the captain, was a confederate pilot. He knew what was happening. The captain was always the same person flying very standardized and similar with every co-pilot. The captain made the co-pilots work the procedures which was the crux. The co-pilots were so busy not to omit a procedure that 90% of the co-pilots dealing with the electric abnormal forgot about the amount of fuel decreasing and losing the big oversight of the scenario. The risk was not the electric abnormal anymore but rather the decreasing, little amount of fuel left. This change of risk perception was the challenge of scenario 2 for the co-pilot. The reason why there are not more crashes is because there is always a more experienced captain on board. The captain has the authority to skip the documentation or even the complete procedures if it seems necessary. This saves time and fuel. Having two people helps to keep the big picture. However, we must keep in mind that such skipping of procedures is not easy and it is in no way recommended by any aircraft manufacturer.

The overall resume of scenario 2 is:

- The automation of the aircraft (A320 ECAM) in combination with the necessary documentation (pilot‘s EFB) was the challenge. Changing from automation to the EFB-documentation and vice versa is distracting, constantly interrupting the work flow of the co-pilot.

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- The awareness of the amount of fuel turned out to be difficult. The decreasing amount of fuel needs to be monitored. It is indicated in kilogram which must constantly be recalculated to remaining minutes of flight time.
- While dealing with the above, the situational awareness of where the plane is in comparison to the airport was another challenge - which is actually the main objective of being a pilot. Questions like “when shall we turn around” or “is there a weather change” or “is there another airport around” where very often not considered by the pilots.

2.1.3. Human Performance Envelope and pilot performance

The HPE concept, restricted to three factors, has been investigated and the experiments demonstrated that the shape of this envelop evolves consistently with the events encountered within the scenarios. As the three factors considered in the project are not totally independent notions, the evolution of the situation often modifies simultaneously all the dimensions of the HPE. At the light of the study, the HPE representation can be considered as a valid concept to assess the constraints that press on the crew. The size of the HPE globally reflects the “pressure” the crew has to cope with. Moreover, psycho-physiological measures can be used to evaluate at least variations of the HPE. Also, the HPE construct can be useful to apprehend the constraints felt by the crew. Nevertheless, further research should be done to investigate other factors and rules to define which factors are the more relevant in a given situation. Ideally the factors kept should not be closely connected but should cover all the main dimensions for a given scenario. For example a factor related to fatigue should be used for a study about long range flights, while it was not necessary in the scenarios taken for this study.

The evaluation of the contribution of new factors to the HPE concept should always be done in experiments allowing a controlled manipulation of these factors. In our study, this part had been done thanks to pre-experiments and scenario 1 where events dedicated to modify one (or few) dimensions of the HPE were used. Controlling the influence of typical events on the shape of the HPE is a necessary step before designing more complex and realistic scenarios. As the HPE combine several connected dimensions it is highly recommended to apprehend how they evolve and combine in elementary situations before using this construct in a more complex scenario.

While the shape of the HPE at one time can be evaluated and used to better describe the pressure of the situation on the crew, it is more difficult to use it to predict performances. This result of the scenario 2 experiment underlines two main concerns.

First, even if the shape of the HPE can be evaluated, it doesn’t really define the edges of the HPE. So while this project gave us methodologies and results about the evaluation of elements that constrained the crew’s performances, we have few means to evaluate the remaining margins for the crew. At that time, tools to assess when the crew reaches the boundaries of the HPE are missing. It is certainly one of the main limitations for the application of this model. Moreover this HPE study confirms that there is no linear relationship between HPE factors and performances. And this is the second concern about a direct use of

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the HPE concept: when the task difficulty and the operational pressure raises, the shape of the envelope is lowered, but the crew adapts its behavior as long as possible to maintain reasonable performances. So it would be beneficial to conduct dedicated controlled experiments to assess if physiological measures could be used to detect when the crew reaches the edge of the HPE and performances really decrease.

The experiment also pinpoints the difficulty to assess performances in a real flight. In many cases, there are no "continuous" performance indicators but rather adequate decisions which are or are not taken by the crew. So a key element is rather how the crew considers all the elements of the situation and makes decisions. Therefore it should be relevant to progress on methodologies and tools to better analyze eye tracking and electro-encephalography data. A combination of these elements could indicate which information is taken (eye-tracking) and how it is processed by the operator.

Finally, the study should also be extended to better apprehend the HPE and performances of the crew, instead of the HPE and performances of the pilot. Indeed, the study has been made with a cooperative captain and the evaluation of the HPE was made on the first officer. It was necessary to develop and test the concept. Nevertheless, in a real flight, performances and decisions are always supported by both crew members and it would be valuable to explore how these elements can be extended to a team. Of course this might be contradictory with the approach of having very controlled experiments. A valid and reasonable balance needs to be found and adapted to the objectives of the respective study.

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2.2. Application of the Human Performance Envelope

2.2.1. For pilot monitoring

Generally, the HPE can be used in two phases: first, to gather data and information about the pilot condition in order to trigger required support and second, to identify difficulties pilots have when operating an aircraft and to validate and certify new cockpit indications and concepts.

Ideally, measuring the different factors of the HPE allows the determination of the condition and finally the performance of the pilot. The nine factors of the HPE are considered to be all of the important factors that can have an influence on the condition of the pilot. Therefore, measuring the complete HPE will allow a complete measurement of the pilot condition.

Within this process of measuring the HPE factors it is important to define the desired condition and behavior of the pilot. This assures the connection between the HPE factors, the condition, and the performance. Measuring the HPE factors without establishing this connection makes it difficult to assess the state of the factors. Furthermore, it makes it difficult to connect the state of the sensors (the psycho-physiological data) with the state of the factors and to determine the boundaries (limits) of the Human Performance Envelope.

Measuring the HPE for pilot monitoring reasons will allow various future concepts to be realized. Reduced crew operations or fully single pilot operations (with or without remote co-pilot) rely on the monitoring of the pilot condition. The detection of a condition with degraded HPE factors is essential for safety reasons. It will trigger adaptive automation or artificial intelligence to take over control or provide required and tailored support or call for the assistance of the remote co-pilot on ground. The HPE includes all the factors that need to be measured to determine exactly the current condition and performance of the pilot.

Pilot monitoring systems are required to provide very reliable data. The identification of a false condition can cause great safety hazards. Therefore, it is highly recommended to use and connect various sensors for the measurement of each HPE factor. Their data should then be compared to be able to identify wrong signals potentially causing the false identification of a condition. Furthermore, various sensors allow a more precise measurement of the level of the respective HPE factor as very often there is not one single sensor and value that is able to unambiguously determine the state of the HPE factor. For example, good sensors to measure the HPE factor workload are physiological data. However, there is not one single physiological data that can always identify the level of workload in all situations. To receive a valid measurement, various physiological data need to be considered and combined (like hear rate and heart rate variability).

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2.2.2. For Human-Machine-Interface design

For the first time, the project applied the HPE to cockpit operation. Previously the HPE has only been used in the Air Traffic Management (ATM) domain. Besides the use for pilot monitoring systems (PMS), the HPE turned out to be a very valuable concept to identify and evaluate problems pilots have when operating an aircraft and to validate and certify new cockpit indications and concepts.

Overall, there is a need for tools creating objective pilot performance data. The measurement of pilots' performance is needed for various reasons. It is required to assess the progress of training and the pass of examinations and check flights for the issuance of licenses and ratings. Additionally, it is an essential requirement for new types of training, like competency based training (CBT). Furthermore, validation activities, like the validation of new operational concepts and human machine interfaces, rely on a precise determination of the pilots' performance in order to allow a correct and valid assessment of the new concepts and technology. This is an aspect which also applies to aircraft certification. Besides the validation and certification of new technology, a valid performance measurement can reveal difficulties pilots have with the technology. The detection of performance deficiencies can clearly highlight necessary design improvements or point out situations where additional support is required by pilots.

The conducted work and results of the project show that the HPE can be applied to cockpit operation and is a valuable methodology to identify and analyse difficult situations pilots can experience, have to cope with and have to manage during flight. This HPE analysis should be augmented by additional methodologies (like cognitive walkthrough or eye-tracking analysis) that represent and quantify in detail the extent to which pilots gather relevant information at the right time. In combination, this will lead to the most precise performance results and most detailed analysis of design problems and necessary design improvements.

When using the HPE for the identification of HMI design problems and for the validation of new HMI designs, it is important to define the desired pilot performance and behaviour. Following this definition, relevant HPE factors can be selected which will be subject of the analysis. The HPE factors again can be observed using specific sensors. Thereby, it is essential to identify the right sensors for measuring each HPE factor. This might not always be a straight forward approach possibly requiring literature review and even pre-tests. In the end, the measured performance results of the pilots can be compared with the desired performance. This comparison will also allow the definition of the boundaries (limits) of the HPE.

Overall, the HPE can support the development of better automation and new HMI designs and their certification by providing sound data and results of certification tests creating scientific evidence about human performance. The HPE is especially valuable for performance based regulation and certification. Additionally, the HPE is able to derive training needs for performance based training and can provide objective data of human performance during training.

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2.3. Human Performance in a Highly Automated Environment

2.3.1. Design challenges for future aircraft

As shown by observing the macro trends affecting air transport like increasing passenger demand - poised to double every 15 years [IATA ref] – and new airspace entrants (unmanned air systems, urban air mobility) a strong drive to increase automation overall is seen, to cope with this pressure. This increasing level of automation will make more acute several challenges affecting decisions and actions when the human is in the loop. In that regard, vehicles of OEMs need tools to assess the human performance in these new complex scenarios, guaranteeing the best overall performance in human-machine collaboration and to keep or increase safety level within the aviation industry expectations.

The concept of human centred automation was formalized by NASA in the 90s (Graeber and Billings, 2019) and extended many aspects that had been practised in the industry. The focus is thus to have automation augment the human capacities and, consequently, the whole system. This paradigm helps guide design decisions where we have humans in the loop.

The question remains how to address incremental automation and autonomy from a human centred perspective. It is well known the dilemma posed for safety by the increased reliability brought by automation, and thus trust of operator in it, and the human capacity to react when called to action. How to insure he is “in-the-loop” and able to do what is needed. Because no system is fool proof, resilience and performance must be embedded into the design. This is the more acute has the need to address an ever more saturated air space, with ever more complex machines within a tighter integrated ecosystem, leads to a natural progression of increasingly highly automated cockpits and other systems. Another challenge is posed by the increased reliability of systems, making system failures rare events to be dealt with. This must be addressed so the crew is in fact able to properly resolve these corner cases.

Regulations rely on the crew ability to handle rare situations and ensure safety. It becomes clear then that to successfully address the demands of future air transport, improved knowledge on the performance of the human within the system must be sought, so the future concepts are effective in augmenting crew’s abilities to engage and ensure efficient and safe flight. In simple terms: provide the best automation in order for pilots to make the best decisions.

To address the challenges previously mentioned, tools and methodologies must be perfected. As a metaphor, “empathy” can be seen as a reference. Methods and tools must be harnessed to account for the human limits during the design process. The concept of Human Performance Envelope is one of such concepts, allowing formalizing and better including the “human” in the overall system design. Coupled with this, training and operations procedures are intimately connected. As automation increases also complexity management should be a training goal, supported by the cockpit design and cockpit design tools.

Hybrid human-machine teams have been shown to deliver higher performance and effectiveness than single human or single machine teams. Factoring the strength and weakness of each (human and automation) is thus crucial to success.

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2.3.2. Aspects of an OEM design philosophy

EMB 110 - Bandeirante EMB E-2 Jets

Figure 1: Embraer cockpit evolution, spanning almost 50 years

Embraer approach to cockpit design was honed with time but always centred on the pilot. Namely, driving to make the airplane support the crew, aiming at achieving true collaborative work. Making workflows smooth, two objectives must be fulfilled: efficient operation and safety. This has been pursued within Embraer across its different aircraft applications: commercial, executive and defence.

In that regard, some design options and philosophy stand out. These are:

- Dark & quiet cockpit, eliminating “noise” and clutter. For instance:
    - “Read and do / see and do”, meaning one page check-lists for all flight phases. These are clear, intuitive, unambiguous so that feedback is right on what is done, ensuring situation awareness and putting the human-in-the-loop;
    - Rotary switches are placed at the 12 o’clock region and also their normal position is placed at “12 o’clock”, in the overhead panel;
- Care is taken to design switches in a way that impede accidental or mistaken toggling;
- The machine provides enhanced feedback to increase situation awareness. For instance, autothrottle feedback provides a clear feedback on what automation is doing.

Regarding automation, having the human in the loop means not only he will be part of the decision process, but must be able to do so, aware of what is happening. Regarding flight envelope protections, for instance, hard limits are clearly advised (e.g. for angle of attack to get pilot). This extends to the soft limits, because pilot can decide to stretch the limits while feedback through controls is provided.

Crews work together, the environment designed to support clear understanding and information flow. An example is active sidestick technology, so the pilot monitoring understands what the pilot flying is doing (e.g., in landing).

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Embraer's concept regarding the role of the pilot is thus simple. Reality is imperfect and thus, failure points will always be present. These can be greatly counteracted by careful design and exploiting of what best is provided by each actor on the overall system. As such, the pilot role is to handle the rare failures in automation, exploiting its inherent ability to better integrate and react to complex, new situations. With increasing levels of automation, care must be taken so the crew is indeed able to address these situations, ensuring safe and efficient flight. Automation, HMI, procedures and training should then enhance the crew, designed to support their work and augment their capacities.

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3 CONCLUSION

Reviewing the results and insights gained throughout the project reveals the validity of the HPE concept and its usefulness and beneficence. The concept helps to monitor the pilots' condition, facilitates the identification of problems pilots can have in difficult complex situations, and supports the validation and certification of new Human Machine Interfaces (HMI) and automation concepts.

Even though this provides great advantages, the application of the concept is not always straight forward. There are a few constraints that need to be considered and dealt with. First of all, the investigation of all nine HPE factors and their interaction can be very complex. Therefore, only the most relevant factors should be selected according to the given situation and scenario in order to reduce the complexity. At the same time, selecting only some of the factors might have disadvantages. There is a risk of ignoring some factors that do have an influence on performance and an interaction with other factors which is not considered or correctly assessed. As a consequence of this, a prediction of the pilots' performance might be difficult or even impossible. Therefore, the balance between the complexity of the measurements and a precise measurement of the performance need to be evaluated and found each time.

A further constraint is the number of sensors selected to measure each factors. Ideally as much sensors should be selected as possible to increase the reliability of the measurements. However, practise this might turn out to be difficult. First of all, there might not be several sensors available for each factor and second, using various sensors increased the amount of data and work to be done to synchronise and analyse them. Again, a balance between the number of sensors and the amount of work required to process the data needs to be evaluated and found given the situation or scenario.

Overall, the project could successfully apply the HPE concept to cockpit operation. I provided great support in identifying difficult situations and in validating new cockpit HMI. Throughout the project various sensors could be identified and tested to measure the different factors of the HPE. Future research should focus on the measurement of further HPE factors and the evaluation of their interaction. Furthermore, future research should focus on the identification, development and testing of additional sensors to measure the various factors.

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4 REFERENCES

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