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HAPTIC FEEDBACK IN PILOT-AIRCRAFT INTERACTION

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HAPTIC FEEDBACK IN PILOT-AIRCRAFT INTERACTION

HMATOVÁ ODEZVA V ROZHRANÍ PILOT-LETOUN

OUTLINE OF HABILITATION THESIS
DESIGN AND PROCESS ENGINEERING

VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ NAKLADATELSTVÍ VUTIUM

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ABOUT THE AUTHOR

Dr Pavel Zikmund was born on July 17, 1982, in Brno, Czech Republic. He received his master's degree from the Institute of Aerospace Engineering (IAE) at FME BUT in 2006. His diploma thesis was entitled Aerodynamic Optimization of the VUT 100 Cobra Aircraft with Respect to Maximum Flight Speed. He continued his doctoral studies at the IAE, focusing on the research area of flight mechanics. In 2013, he defended his Ph.D. thesis, entitled Aerodynamic Characteristics Identification of an Atmospheric Airplane from Flight Measurement Results.

Since 2018, Dr Zikmund has been working as a full-time assistant professor at IAE FME BUT. Dr Zikmund gives lectures and seminars on Flight Mechanics for both Flight performance and Control and stability courses. He recently grants Control and stability, Space Flight mechanics, and Principles of Flight courses. He was also the supervisor of fifteen bachelor's and six diploma theses. He organised several student competitions for both students from FME an also students from grammar schools.

Regarding research activities, Dr Zikmund was the principal investigator in two postdoctoral projects. One was supported by the Czech Science Foundation (GAČR) and the second by the Technology Agency of the Czech Republic (TAČR). He has also participated in several other research projects. Currently, he is a core member of the BAANG project supported by the European Commission. As of August 8, 2024, he has published 5 papers in journals with an impact factor and received 18 citations, with a current h-index of 3 according to Web of Science (WOS). He is a regular reviewer for the *International Conference on Control, Decision and Information Technologies (CoDIT)* conference papers and an occasional reviewer for journal papers, including *Aircraft Engineering and Aerospace Technology* and the *Journal of Aerospace Information Systems*. Dr Zikmund spent six months at EADS Innovation Works (now AIRBUS) in Ottobrunn, Germany, where he designed a gun for accelerating drosophila in a wind tunnel in 2012. He also participated in another short two-month internship at Altoo University in Espoo, Finland, in 2014. Currently, he is at TU Delft in the Netherlands for a 6-month internship, in charge of multidisciplinary design optimization of a morphing wing.

The author's main research topic is presented in this thesis, which originated from his postdoctoral project funded by TAČR. The project focused on haptic feedback in pilot-aircraft interaction. Dr Zikmund has built and led a research team consisting mainly of young doctoral students. The research outcomes include the design of experimental devices capable of providing innovative solutions for pilots’ warning and guidance systems. Despite these achievements, Dr Zikmund plans to shift his research focus toward multidisciplinary solutions addressing sustainability issues.

1 INTRODUCTION

The question posed at the beginning is: "Why do birds never stall but aircraft do?" One might argue that birds are able to flap their wings, but this is only part of the answer. The more crucial point lies in their ability to sense airflow around their bodies. This fundamental difference between birds and pilots in aircraft is noteworthy. Birds have acquired the skill of flight through thousands of years of evolution, while humans have achieved flight in a relatively short period of time due to the efforts of engineers. It is paradoxical that the control mechanisms for small aircraft have seen little change since the First World War [1]. Control sticks and pedals are still used for pitch, roll, and yaw, while significant advancements have been made in aircraft aerodynamics, structures, power units, and systems. The lack of progress in pilot-aircraft interaction presents a challenge, as it contributes to the human factor as a leading cause of accidents.

The performance of human pilots has long been surpassed by automatic elements in aircraft control. The first fully automated landing was achieved with the Boeing 247D in 1945. Furthermore, the US Air Force C-54 accomplished the first transatlantic flight controlled by an autopilot, encompassing take-off and landing, in 1947. Human pilots are constrained by various physiological and mental factors. The reaction time of a human being is approximately 200 ms [2], whereas simple hobby model aircraft autopilots operate at frequencies in the hundreds of Hz range. This significant contrast poses a considerable disadvantage for humans. These facts raise a question: why should we continue to focus on pilot-aircraft interaction instead of replacing the pilot with an autopilot?

We may discover further answers. Let us concentrate on small aircraft. Money emerges as one crucial factor. The installation of an autopilot incurs costs and necessitates actuators, which add extra mass to the aircraft. Another aspect to consider is the purpose of flying. Hobbyists and sports pilots have a desire or obligation to personally control the aircraft. As a result, the human pilot remains the most vulnerable and highly valued component in small aircraft control. Improving pilot-aircraft interaction has been recognized as a promising approach to enhancing safety in small aircraft operations. The solution to the initial question does not lie solely in minor improvements to the current control systems. Instead, a comprehensive and innovative solution emerges from the interdisciplinary connection between aircraft control and human-machine interaction disciplines. The introductory section of this thesis is based on the article [3]. It presents the state-of-the-art of pilot-aircraft interaction field and continue by introduction of the roadmap leading to haptic feedback implementation to pilot-aircraft control loop.

2 PILOT-AIRCRAFT INTERACTION

Aircraft flight control has traditionally relied on mechanical systems. Control surfaces on an aircraft are mechanically linked to the pilot using rods, levers, cables, and pulleys. The main control surfaces include the elevator, responsible for controlling the pitch or up-down rotation, the ailerons, which control the roll or spinning around the front axis, and the rudder, used for controlling the yaw or right-left turning. Figure 1 illustrates an example of the control mechanism found in a Cessna 172N aircraft.

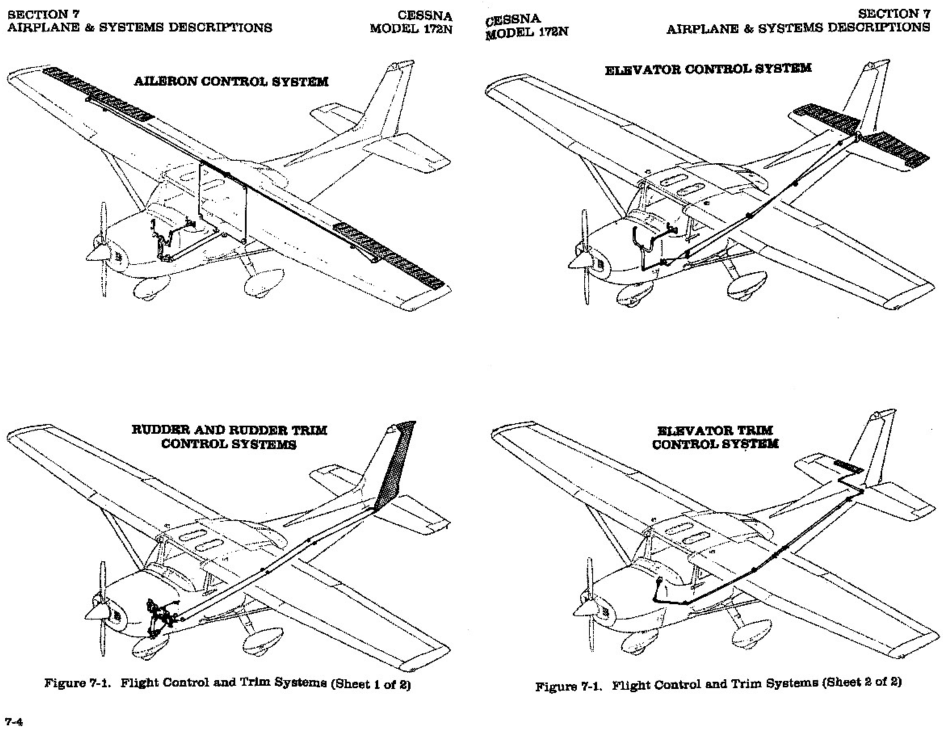

Figure 1: Cessna 172N control system from Pilot operating handbook [4]

These controls function as the forward path of the control system. However, the feedback path is equally essential. Feedback is not solely conveyed through force sensations in the control stick and pedals. Various other methods are employed to provide pilots with feedback regarding the flight, including flight instruments, structural vibrations, auditory cues, inertial forces, and visual contact with the ground. Feedback can be categorized based on the modality used to perceive information.

The modalities utilized for pilot feedback in aircraft control, as well as the corresponding psychological aspects, have been discussed in the research paper [3]. Among these modalities, vision plays a crucial role. Pilots rely on their vision to read flight instruments, maintain visual contact with the ground, navigate, manage air traffic, and perform certain communication-related tasks. The sense of touch is another important modality. Pilots perceive forces and vibrations through the aircraft controls, as well as inertial forces and vibrations through their seat. Finally, hearing is a significant modality employed by pilots for communication, as well as for monitoring aircraft sounds and various warning signals.

Pilot-aircraft feedback and interaction are essential not only in conventional control systems with mechanical links but even more in fly-by-wire control systems. In a fly-by-wire control system, pilot inputs are processed by a computer, which then determines how to manipulate the control surfaces. There is no direct connection between the control stick, pedals, and control surfaces. Despite the fact that fly-by-wire is not a new concept, its adoption in general aviation has been slow [5]. The system offers the most benefits for military and large aircraft. However, the emergence of Urban Air Mobility aircraft concepts has made the spread of fly-by-wire systems among small aircraft increasingly relevant.

2.1 PSYCHOLOGICAL ASPECTS OF HUMAN-MACHINE INTERACTION

This chapter delves into three key psychological aspects that shape the HMI: situational awareness, workload, and divided attention. Understanding these factors is essential for designing interfaces that optimize human performance, enhance user experience, and promote efficient and successful interactions between humans and technology.

Situational awareness

Situational awareness, as described by Endsley [6], [7], refers to "knowing what is going on around you." Endsley presented three levels of situational awareness. The first level is the perception of the elements in the environment. This means a pilot needs to be aware of factors such as speed, altitude, weather conditions, and air traffic, among others. The second level involves the comprehension of the current situation, which means understanding the significance of the parameters from the first level. The third level, known as projection, is the ability to forecast future events in a certain situation. For example, a pilot must anticipate potentially dangerous flight regimes, weather changes, or air traffic conflicts.

Wickens [8] discussed three concepts of situation awareness: spatial awareness, system awareness, and task awareness. Spatial awareness is associated with a pilot's monitoring and control of attitude and position variables. These variables are interrelated and involve time lags in the flight dynamics. System awareness pertains to a pilot's understanding of complex onboard systems. Task awareness is closely connected to task management, where a pilot performs four distinct generic classes of tasks: aviating, navigating, communicating, and managing systems [9].

Workload

The concept of workload does not have a universal definition. It can be simply defined as the demand placed on the human operator. A more detailed definition, as provided by Eggemeier et al. [10], states that "mental workload refers to the portion of the operator's information processing capacity or resources that is actually required to meet system demands."

Miller [11] presented a comprehensive study on workload and its assessment. Workload measurement can be classified into three main categories: psychological, subjective, and performance-based. Subjective scales are often used in experimental settings. Two common methods of unidimensional workload assessment are the Cooper-Harper Scale and the Overall Workload Scale. The Bedford scale, which was developed specifically for pilots and drivers, is one of modifications of the Cooper-Harper scale. The use of unidimensional methods is preferred due to their simplicity. In addition to these subjective scales, the physiological method based on mean pulse rate measurement offers good sensitivity in workload assessment [12].

Multidimensional measures offer a more sophisticated assessment of workload. The most commonly used method is the NASA Task Load Index Scale (NASA-TLX). NASA-TLX requires participants to perform paired comparison tasks and assesses workload across six dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration. To address the time-consuming analysis involved, a modified version of the method called the NASA Raw Task Load Index has been developed.

Workload levels change during a typical flight, with the highest workload usually identified during take-off, approach, and landing phases, as well as during any emergency situations. The workload in a cruise flight regime is typically of lower value. Workload also depends on the pilot's capacity to execute required tasks during the flight. That means, pilot's workload during longer-duration flight regimes might increase due to rising pilot fatigue and decreasing pilot performance.

Divided attention

Divided attention refers to the ability to process multiple pieces of information simultaneously. It is often used interchangeably with the term "multi-tasking." However, it is important to note that divided attention can lead to a decrease in the amount of attention allocated to each individual task when multiple focuses are present simultaneously. In the context of aviation, a common example of divided attention is the pilot's need to simultaneously engage in aviating, navigating, and communicating. These tasks are processed by the pilot with a priority hierarchy known as "aviate-navigate-communicate" [9]. Extended model is known as ANCS, which add "systems management" as a task with the lowest priority.

One aspect that influences the divided attention is modality. Our work is focused on haptic guidance and cannot neglect the visual tasks necessary for aircraft control. The report by Wickens [13] discussed cross-modal divided attention. Wickens concluded that divided attention to the ear and eye can be more efficient than eye-to-eye and ear-to-ear divided attention.

2.2 PHYSIOLOGICAL ASPECTS OF TOUCH

Physiological aspects of touch play a significant role in human-machine interaction, alongside psychological and technical aspects of the man-machine system.

Touch mechanoreceptors

Touch mechanoreceptors are sensory receptors embedded in the outer and underlying layers of the skin. These receptors come in various types, each with its own characteristics such as the type of stimulation to which they respond, the size of their receptive field, and the rate of adaptation, which can be fast or slow. The different types of touch mechanoreceptors include [14]:

- Meissner corpuscle: These receptors are involved in touch and grip control, detecting slipping objects.
- Merkel cell neurite: These receptors are responsible for perceiving touch, as well as form and texture.
- Ruffini endings: They respond to pressure and provide information about the shape of the hand and object motion.
- Pacinian corpuscle: These receptors sense pressure and vibrations and pressure when grasping objects.
- Hair follicles: Found in hairy skin, these receptors are involved in the perception of touch.

The first four types of mechanoreceptors are located in the palm and fingers, but they're not evenly distributed. This means that haptic feedback needs to be concentrated to offer the best cues at the intended point of contact. Furthermore, how a haptic feedback device is gripped can influence how these cues are perceived. Another key point is that optimal haptic feedback performance is achieved when the device activates a greater number of mechanoreceptors. For instance, a combination of shape and movement, or pressure cues, provides a more comprehensive feedback experience compared to vibrations alone.

Touch stimuli thresholds

The sense of touch operates within limitations in both time and space resolution. Just noticeable difference, also referred to as two-point discrimination, denotes the minimum distance between two stimuli detectable by humans. This value varies, ranging from a few millimetres on the fingertips to roughly ten times more on the shoulders, back, and legs. The lowest threshold value is 2.5 mm at the fingertips, while the threshold for the trunk is approximately 40 mm [14].

Similarly, sensitivity in the time domain is also constrained. The threshold sensitivity for recognizing two stimuli is 5 ms for touch, although this value varies for other modalities. In comparison, the detectable threshold for vision is 25 ms, while for audition (hearing) it is an impressively low 0.01 ms [15]. The mentioned results are average values. The real value depends on many aspects such as age or cue intensity.

Reaction time

Numerous research studies have been conducted to measure reaction time (RT). The values for simple reaction time typically range from 140 to 270 ms. Several factors influence RT, including the type of stimulus, such as stimulus intensity, foreperiod time, age, gender of the participant, and more. It's important to note that RT can vary depending on the modality of the stimulus. Auditory stimulus reactions tend to be slightly faster, while visual stimulus reactions are slightly slower compared to touch stimulus reactions [2], [16]. The reaction time significantly increases when any decision is required.

2.3 BIO-INSPIRED AIRCRAFT CONTROL

The paper [3] introduced a new idea of small aircraft control improvement. The inspiration for the control system modifications comes from the natural world, specifically the airflow feeling sensation by bird or insect neural system. The proposed concept leads to an artificial airflow sensation of a pilot. The main paper goal was to specify the background and requirements from various fields of interest. The review section provides an overview of natural and artificial flow sensors, haptic actuators, and recent applications. Additionally, the pilot sensory load is discussed, and a gap in aircraft control is pointed out. Two scenarios for bio-inspired modifications are proposed: a full-extent scenario (ideal but currently impractical) and a realistic scenario. The realistic scenario has the potential to improve controllability, reduce pilot workload, and enhance situational awareness by creating an artificial feeling of aerodynamic flow characteristics. This connection of human-machine interaction with aircraft control reveals new possibilities for aircraft control. The basic idea is presented in Figure 2.

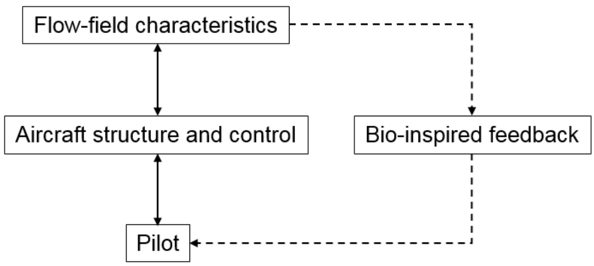

Figure 2: Bio-inspired feedback schema [3]

The future work proposed in this paper involves the real-world implementation of the suggested bio-inspired aircraft control concept, followed by extensive flight testing. However, achieving the full-extent scenario of bio-inspired aircraft control system, representing an ideal pilot-aircraft interaction, is likely beyond the current capabilities of aircraft technologies. Therefore, the upcoming research was focused on the pragmatic applications of the realistic scenario.

2.4 RESEARCH GOALS

In view of the literature search presented in [3], the following scientific objectives for ongoing research were set:

- To improve the pilot's situational awareness of airflow around the aircraft.
- Identify a method for tactile guidance to help the pilot achieve optimal flight modes or receive stall warnings.
- Design and manufacture a system for implementing tactile guidance into aircraft.

3 EXPERIMENTS WITH HAPTIC FEEDBACK JOYSTICK

With the aforementioned background, the practical part of the pilot-aircraft interaction research began. This section introduces three subsequent research papers and a practical hardware solution declared as two utility models.

3.1 DIRECTIONAL VIBROTACTILE FEEDBACK

At first, a device was designed and tested to facilitate haptic feedback from the aircraft to a pilot through directional vibration feedback applied to a joystick. The results of this experiment are described in the paper[17]. The task involved the reaction to the directional vibrations of segments mounted on the joystick by an intuitive reaction. Out of all 19 participants, 18 selected a direction for the vibrations, either in the same or opposite direction. Participants reacting in the forward direction (13 out of 18) achieved better results in terms of error rate and reaction time compared to those reacting in the reverse direction. The primary hypothesis, which posited that humans can discern directional vibrations and respond accordingly, was confirmed, with an error rate of 5 %.

In this context, we explore the potential functions of the pilot-aircraft haptic feedback device, focusing on two main functions: warning and guidance. The warning function is essential for enhancing situational awareness in various aspects, including spatial awareness, system awareness, and task awareness. In terms of spatial situational awareness, the provision of directional feedback would be highly valuable. For instance, during collision avoidance manoeuvres, the haptic feedback device could convey the direction of nearby aircraft. Additionally, warning functions can also be non-directional in nature. A common example of such a warning is the stall warning, which does not require specific directional cues. On the other hand, the guidance function relies heavily on the use of directional haptic cues.

3.2 VIBRATION PATTERNS AND MODULATION IN THE GUIDANCE TASK

The second experiment conducted with directional vibrations focused on finding the best vibration patterns for a guidance task, as described in [18]. The task involved guiding the joystick to randomly generated front-back positions. The same hardware used in the previous research was utilized. The experiment compared guidance methods based on duration and rhythm modulation of vibrations. Additionally, the impact of contra vibrations just before reaching the target position was analysed. The experiment revealed that duration modulation of vibration, proportionate to the distance between the actual and target joystick position, yielded the best results. Furthermore, the effect of contra vibrations, aimed at compensating for human delay in haptic perception and reaction, was examined. However, the contra vibrations did not demonstrate any significant improvement and even led to a decrease in participants' performance.

Despite these findings, directional vibrations did not demonstrate convincing performance in the guidance task. As a result, we have developed a new method for joystick guidance that incorporates haptic feedback. This approach involves the use of a sliding element that moves beneath the operator's finger, replacing the directional vibrations. The experiment described in the publication [19] showcased a significant improvement in both the speed and accuracy of guidance. The hardware used in this method is depicted in Figure 3.

Figure 3: Sliding element and vibration motors joystick handles [19]

Joystick guidance using a sliding element

The mentioned paper describes a comparison between two guiding methods: vibrations and a sliding element. The directional vibration joystick was replaced by new hardware based on the Mad Catz Pacific AV8R joystick. Two different handles could be mounted to the body of the joystick. The first handle had a similar position of vibration motors as the previous hardware. The second handle contained two servos that moved the sliding element in and out of the handle under the operator's fingers. The feedback was predominantly provided by the shape of the relative position interface between the reference and the sliding element, with partial feedback derived from the force exerted by the sliding element on the fingers when moving towards the operator's fingers.

The guidance methods have been tested on two different tasks. Task 1 involved guiding participants to 30 randomly generated front-back joystick positions. Task 2 consisted of a 30-second recording of the joystick's forward-backward movement. Task of participants was to follow this pre-recoded trajectory where the sliding element represented deviation from the trajectory. In this task, participants were guided by haptic feedback to follow a continuously changing target position. Similar guidance tasks were used in the subsequent study [20], although with slightly different parameters. The first task in the subsequent study included only 20 random positions (Figure 4), while the duration of the continuously changing target position in Task 2 was extended to 60 seconds (Figure 5).

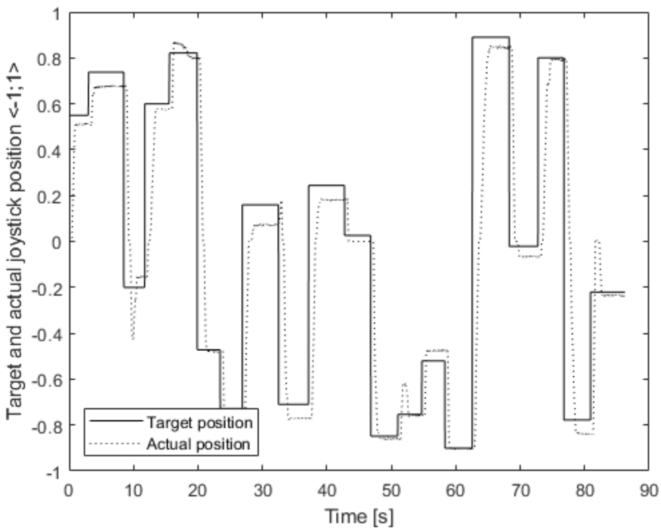

Figure 4: Sample recording of the guidance to randomly generated forward to backward joystick position tested in Task 1 [20]

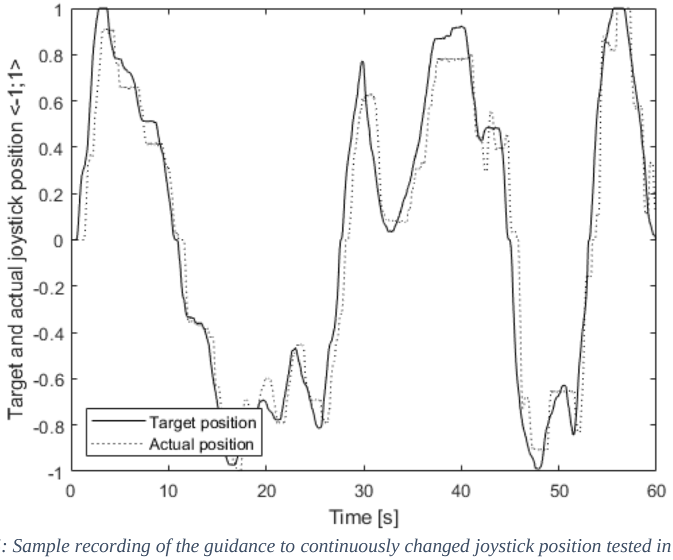

Figure 5: Sample recording of the guidance to continuously changed joystick position tested in Task 2 [20]

The performance of the participants in the guidance tasks was evaluated based on their reaction time and the mean error between the target and actual joystick positions. The mean reaction time values were 1.904 seconds (SD = 0.37s) for the vibration method and 1.548 seconds (SD = 0.48s) for the sliding element method. The sliding element method demonstrated an improvement in guidance accuracy, as measured by the mean error between the actual and target position. For the vibration method, the average error was 10.61% (SD = 2.58) of the joystick range, while for the sliding element method, the average error was 6.671% (SD = 1.12) of the joystick range. This value reached using the sliding element method means a competitive result in comparison to other tactile guidance methods [21], [22].

In addition to the quantitative results, the haptic feedback was assessed individually by the participants. The sliding element was generally considered intuitive, though one participant expressed a preference for the reverse orientation of the element movement. Both methods were deemed effective for reaching the target position, with the sliding element approach assessed as more efficient than the vibration method in terms of achieving the target with minimal effort. Beyond these findings, the results also pointed to another issue for further analysis. As mentioned by [23], individuals continuously adapt to constant tactile input, and the perception of multiple tactile inputs can evoke specific sensations. These observations give rise to two challenges. The first challenge involves personalizing the haptic feedback. Functions that convey tactile information should accommodate individual customization, creating an opportunity for adaptive control system, as discussed in the future work section. The second challenge concerns investigating the learning process and participant adaptation over the course of long-term experiments. The learning process was measured and discussed in the research paper [20].

4 HARDWARE DESIGN

At this point, two separate devices to provide haptic feedback about flight parameters to a pilot are presented. Both the active control stick and pedals have been declared as utility models: CZ 32930 U1_2019 [24], CZ 33800 U1_2020 [25]. The first one has already been shown in Figure 3. Figure 6 illustrates the joystick handle (no. 1) with the sliding element (no. 2), which is mounted on two servos (no. 3) along with gears (no. 4). Additionally, the control unit (no. 5) is depicted. Furthermore, Figure 7 provides a detailed depiction of the gearing mechanism of the sliding element. This mechanism enables both symmetrical and asymmetrical movements.

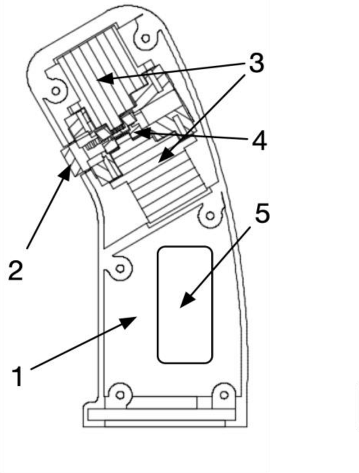

Figure 6: Joystick handle with two servos powering the sliding element [24]

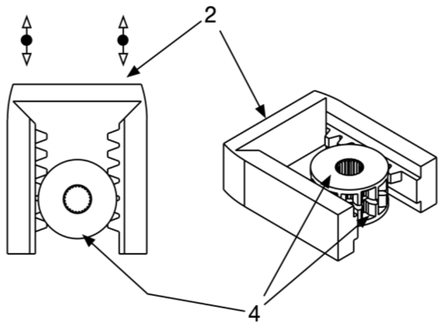

Figure 7: Sliding element gearing mechanism which allows symmetrical and asymmetrical movement [24]

The original idea was to convey the feeling of Angle of Attack through the symmetrical movement of the sliding element. As for the angle of sideslip, the asymmetrical movement was intended to be used. Another option to provide the sensation of angle of sideslip was presented through the second utility model, which incorporates active extensions for the rudder pedals equipped with vibration motors. This system was inspired by the US patent [26], where the system tactically alerts a pilot about an uncoordinated turn through vibrations in the pilot's seat. Subsequently, after conducting experiments, we discovered that a very similar patent had been published [27]. Figure 8 shows an example of the placement of vibration elements (no. 2) within one of the pedals (no. 1) of the aircraft foot control, specifically for the flat pedal type. The vibration elements are mechanically secured with flexible material (no. 3) to provide vibration damping. This arrangement effectively prevents vibrations from propagating between pedals. Alternatively, Figure 9 presents an alternative solution for the rod pedal, illustrating the location for housing the vibration motor itself (no. 4).

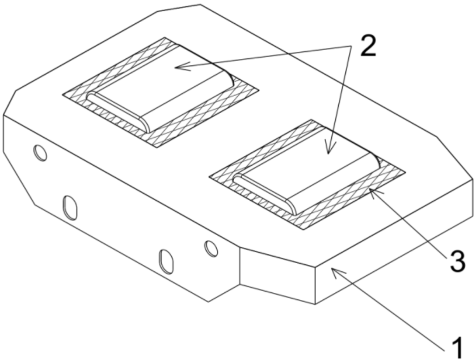

Figure 8 A sample solution of flat-type pedal with vibration elements [25]

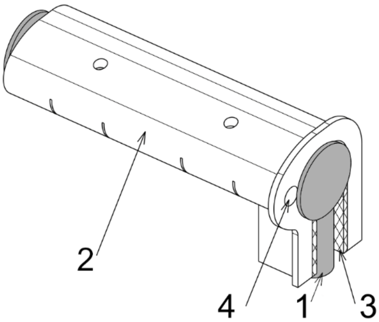

Figure 9: A sample solution of rod-type pedal with vibration motors position [25]

5 FLIGHT SIMULATOR AND FLIGHT TESTS

Hardware manufacturing and tuning, through the first experiments, allowed us to advance the project to a higher technological readiness level. Subsequently, it was time to test the devices in a flight simulator and conduct flight tests. Initially, we carried out flight simulator tests, followed by flight tests using an ultralight aircraft WT9 Dynamic. The flight test results were first published in the EASN conference proceedings [28], despite the order of the tests. Later, an extended version of the paper was published [29], which included a description of the flight simulator test and its results. In this thesis, the chronological order of events is followed.

5.1 FLIGHT SIMULATOR TESTS

Twelve participants holding piloting licenses participated in a flight simulator experiment. The test setup is shown in Figure 10. The objective was to navigate a series of gates at a low altitude above water, conducting three flights with different haptic device configurations. The order of these flights was determined using the Latin square method. Participants were instructed to maintain a low airspeed and minimize side-slip angle. In the second part of the experiment, they executed take-off and climb manoeuvres, during which an unexpected engine failure was introduced. The participants' task was to safely land the aircraft. Half of the participants performed this task with haptic feedback, while the remaining half performed it without haptic feedback. Throughout the experiment, participants completed a questionnaire to evaluate their perception of feedback received.

Figure 10: Flight simulator setup on the left side with rudder pedal detail on the right side [29]

The experiment evaluation revealed unexpected results. The assessment of workload indicated that flights without haptic feedback had the lowest workload, likely due to insufficient training. The hypothesis that haptic feedback had no significant impact on pilots' ability to fly with minimal side-slip was not rejected. Correlation analysis between questionnaire responses and flight data revealed a weak correlation between pilots' assessment of haptic feedback helpfulness and cumulative side-slip performance. Pilots who had poorer cumulative side-slip performance rated the helpfulness of haptic feedback with AoS indication on the joystick higher, whereas those who achieved better cumulative side-slip rated the helpfulness of haptic feedback with AoS indication on the rudder pedals lower. Furthermore, there was a strong correlation between participants' flight simulator hours and cumulative side-slip across all flights, indicating a reliance on simulator experience.

5.2 FLIGHT TEST

Flight testing differs significantly from flight simulator experiments. Both safety and economic reasons led to conducting just one pilot measurement at a safe altitude and speed. The flight measurement had the following goals:

- To evaluate the readability of haptic feedback in flight, where the aircraft structure transfers vibrations from the flow field around the aircraft and from the power unit.
- To measure whether the indication of sideslip by vibration pedals could improve flight control during 360-degree turns. This measure was analysed based on the cumulative side-slip angle in turns, comparing flights with and without the haptic feedback.

Only the vibration pedals had a sideslip indication function. The sliding element in the control stick conveyed only the angle of attack through symmetrical movement. The installation of haptic feedback devices is shown in Figure 11.

The flight test showed that the haptic feedback system can decrease the mean value of the sideslip angle during turning. However, this result was not statistically significant. The sliding element of the control stick was described by the pilot as sensitive but with a disturbing continuous wobbling movement. This movement was partially caused by insufficient filtering of the angle of attack (AoA) input in the control unit and coarse digital conversion, resulting in insensitive AoA input. The readability of the sliding element in the control stick and the vibration rudder pedals was assessed positively.

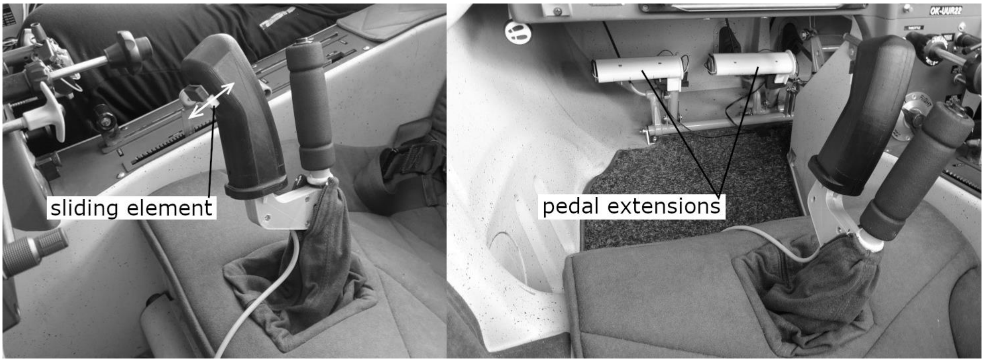

Figure 11: Sliding element and vibration pedals mounted in the aircraft cockpit [29]

The flight test revealed some future steps that should be taken to maximize the benefits of haptic feedback in aircraft control. Changes to filtering and digital conversion are expected to address the issue of the sliding element's wobbling movement. The vibration threshold value needs to be optimized to prevent excessive haptic information that may disturb the pilot without providing any further positive effects. Training in the use of haptic feedback is necessary to maximize the gains from its utilization.

The recommendation from the paper's conclusions for future experiments was to involve a longer training period to mitigate the learning effect and investigate the effects of the system on pilots who are properly trained to use it. Therefore, the following experiments aimed at defining the learning curve have been prepared and executed.

6 LEARNING EFFECT MEASUREMENT

The demand for learning speed in using haptic feedback led to the conduction of a subsequent experiment [20]. The study presents the results of the learning effect under purely tactile guidance without visual feedback. Twelve participants conducted two guidance tasks in twelve sessions to analyse the learning effect. The paper demonstrates an improvement between sessions in guidance accuracy, response time, and self-assessed workload.

The participants' responses were qualitatively assessed, describing characteristics such as overshoot, non-minimum phase, failure to reach the target position, and correct responses. The count of all response characteristics across all 12 sessions is depicted in Figure 12. It is evident that the count of correct responses exceeds 90 % in the last three sessions.

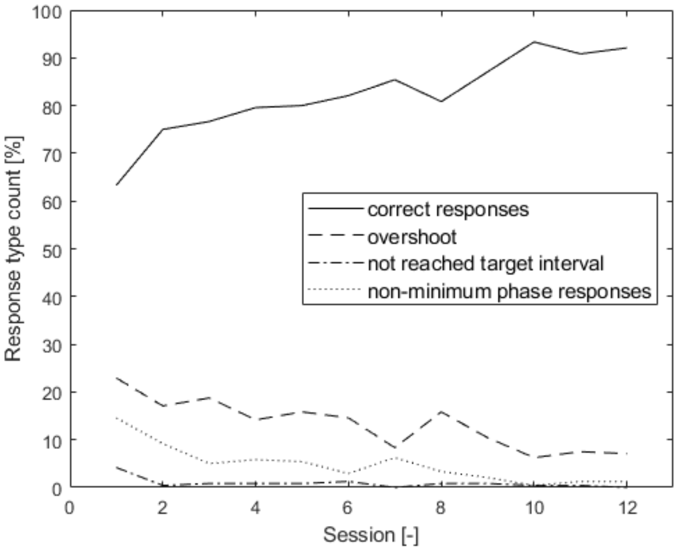

Figure 12: Count of all participants' response characteristics [20]

The results were analysed using repeated measures ANOVA. The participants' performance progress between sessions demonstrates an improving trend, especially in the first seven sessions. The average error between the actual and target positions and the self-assessed workload were parameters significantly influenced by the training. However, the reaction delay was not significantly influenced by training, and the improvement in time to reach the target position was only observed between the first two sessions.

The average error between the target and actual joystick positions in Task 1 decreased from 3.39 % (SD = 1.08) of joystick range in the first session to 2.16 % (SD = 0.51 %) of joystick range in the last session. The average error in Task 2 decreased from 6.43 % (SD = 1.83) of joystick range in the first session to 4.58 % (SD = 1.16 %) of joystick range in the last session.

6.1 THE FEEDBACK DEPENDENCY AND SUPPRESSION

The use of haptic feedback in training raises a critical safety question: What happens if the haptic feedback system malfunctions? A definitive answer requires comprehensive research. However, some studies provide insights into potential outcomes. Deldycke et al. [30] developed a tool to assist with manual flare manoeuvre training. While their findings showed only slight improvements at the start of the training, the haptic force-feedback contributed to a more consistent initiation of the flare. Crucially, their results did not indicate any dependency of the acquired skills on the haptic enhancements.

On the other hand, recent research efforts have also focused on improving haptic feedback in fly-by-wire controls. For example, van Baelen et al. [31] described a system for flight envelope protection using haptic feedback, which integrates both force and vibrations in the control stick. This system aids pilots in avoiding flight envelope speed and load factor limits, particularly during transitions to alternative control laws. Their study concluded that the training created a dependency; pilots' performance degraded after the removal of force-feedback. However, the performance related to vibrations was not impacted by this dependency.

These outcomes highlight the distinct types of mechanoreceptors responsible for detecting various tactile cues. Pacinian corpuscles are responsible for sensitivity to vibration and pressure and Meissner corpuscles are responsible for sensitivity to light touch. Both types of mechanoreceptors are rapidly adapting [32], making them potentially useful in tasks that depend in tasks which depend on quick, precise feedback. On the other hand, Ruffini endings are slow adapting mechanoreceptors and provide valuable feedback for gripping objects and feeling finger position and movement. Exploitation of Ruffini endings in haptic feedback could be beneficial in continuous tasks, ensuring stability and precision in prolonged contact scenarios.

A second challenge associated with applying haptic feedback to a moving hand is the variability in perception. This is also related to the speed of adaptation of mechanoreceptors to different tactile sensations. While haptic guidance has been shown to enhance guidance accuracy as indicated in [33] and [34]. Voudouris and Fiehler [35] find out that tactile stimuli perception on a moving hand can be systematically diminished. This reduction may be due to the brain's limited ability to process sensory information that isn't pertinent to the immediate task. In the experiments we conducted, the movement of the hand and the sliding element are intertwined, creating a closed control loop. Therefore, we posit that in such scenarios, there might be an increase in sensitivity, contrasting the reduced sensitivity observed during non-essential movements.

Another aspect affecting the perception of haptic feedback on the control stick handle is the grasping method. Harris et al. [36] discovered that tactile learning is topographically distributed and varies for different tactile cues. While the learning of force and roughness perception partially transfers to neighbouring fingers, the discrimination of vibration frequencies does not spread to other fingers. This finding should be considered in the design of haptic feedback devices that allow for variable grasping methods.

6.2 HUMAN CENTRED DESIGN

The paper [37] concludes the previous research conducted on haptic feedback in pilot-aircraft interaction and proposes a roadmap for further development in this research topic. Some possibilities of Human-centred design (HCD) application to aircraft control are introduced in the paper. Principles and guidelines for human-centred automation in aircraft and aviation systems were outlined by Billings [38]. This work was motivated by aircraft accidents associated with 'Loss of Situational Awareness,' attributed to main factors such as complexity, coupling, autonomy, and inadequate feedback. These factors led to following principle: Operator must be involved and informed, must be able to monitor the system and automation must be predictable. Another principle is focused to automation, which must monitor the human. These principles should be considered in application of the haptic feedback system in light cockpit aircraft. Apart from these principles, classical usability plays important role in human-machine interaction.

Nielsen [39] defines usability as “a quality attribute that assess how easy user interfaces are easy to use”. These aspects include Learnability, Efficiency, Memorability, Low Error Rate, and Satisfaction. In the context of pilot-aircraft interaction, HCD focuses on the entire process of cockpit design, including the context of aircraft systems and flight procedures. In contrast, Usability is more concentrated on the pilot-aircraft interface, emphasizing its efficiency and satisfaction. These usability aspects could be utilized to optimize the pilot-aircraft interface, which is designed with HCD principles in mind.

By merging HCD and usability principles with the benefits of haptic feedback, potential applications were identified: notifications, feedback, guidance, and conveying complex information. The goal is to optimize pilot capacity and reduce visual overload in difficult or emergency situations by transferring part of the information flow from the visual to the haptic modality. The paper [37] presents three levels of haptic feedback applications. The first deals with stall warning, the second level is linked to feedback and guidance, simulating the pusher function. The last, third level also provides feedback and guidance, serving as a complex flight director system. The difference from the second level is that the system must estimate or know the optimal or target flight trajectory, while in the second level, it only reacts to a high angle of attack.

7 CONCLUSIONS

This thesis offers a comprehensive review of published papers in the field of pilot-aircraft interaction using haptic feedback. The overarching objective and motivation for this research were to enhance pilot-aircraft interaction, ultimately reducing human error as the primary cause of flight accidents. The know-how in commented papers evidences a progress in the goals set out in Chapter 2.4.:

- Improvement of pilot's situational awareness of airflow around the aircraft.
- Identifying a method for tactile guidance and stall warnings.
- Designing and manufacturing a system to implement haptic feedback into aircraft.

Initially, the state of the art and a theoretical framework were presented. Subsequent research focused on elementary haptic actuators and human interaction. This led to the development of innovative devices for rudder pedals and aircraft control sticks capable of providing haptic feedback to pilots. Then, these devices were experimentally tested using flight simulators and flight tests. A major contribution of this work is the assessment of new methods for guidance tasks. The sliding element method was found to significantly outperform vibrations; however, vibrations still hold value for warning systems. The experiments also revealed the need for individualized settings and training in the use of haptic feedback. This has been examined and has yielded useful materials for the necessary training to maximize the benefits of haptic guidance.

Based on these findings, future research directions were proposed in the published papers. These primary objectives were identified for subsequent projects:

- Personalisation of haptic feedback, exploitation of adaptive control systems in flight control.
- Identifying a suitable solution for portability of the installation within aircraft.
- Implementation haptic guidance in a flight director system.
- establishing a viable route for system certification (using certification specifications CS-VLA or CS-23).

In conclusion, there is potential to apply this knowledge to the control of Urban Air Mobility and fly-by-wire control systems, which are gradually being adopted in the General Aviation sector. The results may also have applications beyond aviation. The developed haptic guidance method could be utilized in various teleoperation tasks or in assistive technology for visually impaired individuals.

NOMENCLATURE

Symbol	Meaning	Unit
AoA	Angle of Attack	[rad/deg]
AoS	Angle of Sideslip	[rad/deg]
CS	Certification Specifications	
HCD	Human-Centred Design	
HMI	Human-Machine Interaction	
NASA-TLX	NASA Task Load Index Scale	
RT	Reaction Time	[s]
SD	Standard Deviation	
VLA	Very Light Aeroplanes	

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Haptic Feedback in Pilot-Aircraft Interaction

ABSTRACT

The human factor is often cited as the leading cause of aviation accidents. Despite longstanding awareness of this issue, the incidence of human factor-related accidents in general aviation has seen little reduction. This thesis presents a novel multidisciplinary approach to addressing this problem. The pilot-aircraft interface was identified as a potential way for reducing the risk of accidents attributable to human factors. The goal of this work was to design a system that would enhance the communication of flight-related information to the pilot, particularly regarding the flight variables and the airflow around the aircraft. Tactile feedback elements were integrated into the conventional manual mechanical control of the aircraft. This commentary of published papers reviews the evolution of the haptic feedback elements from their initial development and testing for integration into the aircraft's primary control system to the system's verification through flight simulation and flight testing. While the proposed system has evolved into utility models, challenges remain regarding its portability, ease of integration into aircraft, and particularly, meeting system certification requirements for commercial aviation use.

Hmatová odezva v rozhraní pilot-letoun

ABSTRAKT

Lidský faktor je označován jako nejčastější příčina leteckých nehod. Ačkoliv tato skutečnost je známa už delší dobu, v rámci všeobecného letectví se počet nehod s podílem lidského faktoru daří snižovat jen pomalu. Tato práce přináší unikátní multidisciplinární přístup k této problematice. Jako místo pro možné snížení rizika nehod způsobených lidským faktorem bylo identifikováno rozhraní pilot-letoun. Cílem práce bylo vyvinout systém, který by pilotovi předával lépe informace o letových veličinách a charakteru proudění kolem letounu. Do klasického manuálního řízení letounu byly zakomponovány prvky hmatové zpětné vazby. Tento komentář vydaných publikací shrnuje cestu od prvotního vývoje a testování hmatových zpětnovazebních prvků do primárního řízení letounu až po ověření systému pomocí letového simulátoru a letovou zkouškou. Ačkoliv byl navržený systém dotažený do stavu funkčních vzorků, před komerčním využitím v letectví je třeba vyřešit další otázky týkající se přenositelnosti a snadnosti zástavby systému do letounu a zejména plnění požadavků pro certifikaci systému.