Brno University of Technology
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Letecký ústav

Haptic Feedback in Pilot-Aircraft Interaction

Habilitation Thesis
Habilitační práce

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Brno 2024

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. Nejprve šlo o vibrační zařízení, které bylo poté doplněno o výsuvný člen v madle řídicí páky, kterým lze předávat spojitou informaci například o úhlu náběhu. Tento systém byl navržen pro dvě základní funkce, a to navádění do optimálního případně bezpečného režimu letu a varování před pádem. 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. Hodnocení účastníků experimentu bylo většinově pozitivní, nicméně výsledky dále vedly k výzkumu efektu učení za účelem stanovit délku tréningu pro využití přínosů, které systém nabízí. 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.

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, initially in the form of a vibration device. This was later augmented by a sliding element inside the control stick handle, capable of conveying continuous information about variables such as the angle of attack. The system was designed to serve two primary functions: guiding the pilot towards optimal or safe flight modes and providing stall warnings. 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. Participants' evaluations of the experiment were largely positive. However, the results also prompted further research into the learning effect, with the aim of determining the training duration required to maximize the benefits offered by the system. 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.

Acknowledgement:

I would like to extend my gratitude to my wife Zu, children Ma and Dodo, and my parents for their support and love in my day-to-day life. Additionally, I wish to express my thanks to my colleagues Ing. Michaela Horpatzká and Ing. Lukáš Dubnický, who collaborated with me on project focused on haptic feedback and our joint publications. Special thanks belong to my colleague, Ing. Miroslav Macík, Ph.D., who introduced me to the topic of Human-machine interaction and provided valuable feedback to this thesis.

CONTENTS

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 (Al-Lami et al., 2015). 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 (Kosinski, 2008), 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 **(Hab-1)**. 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.

1 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.

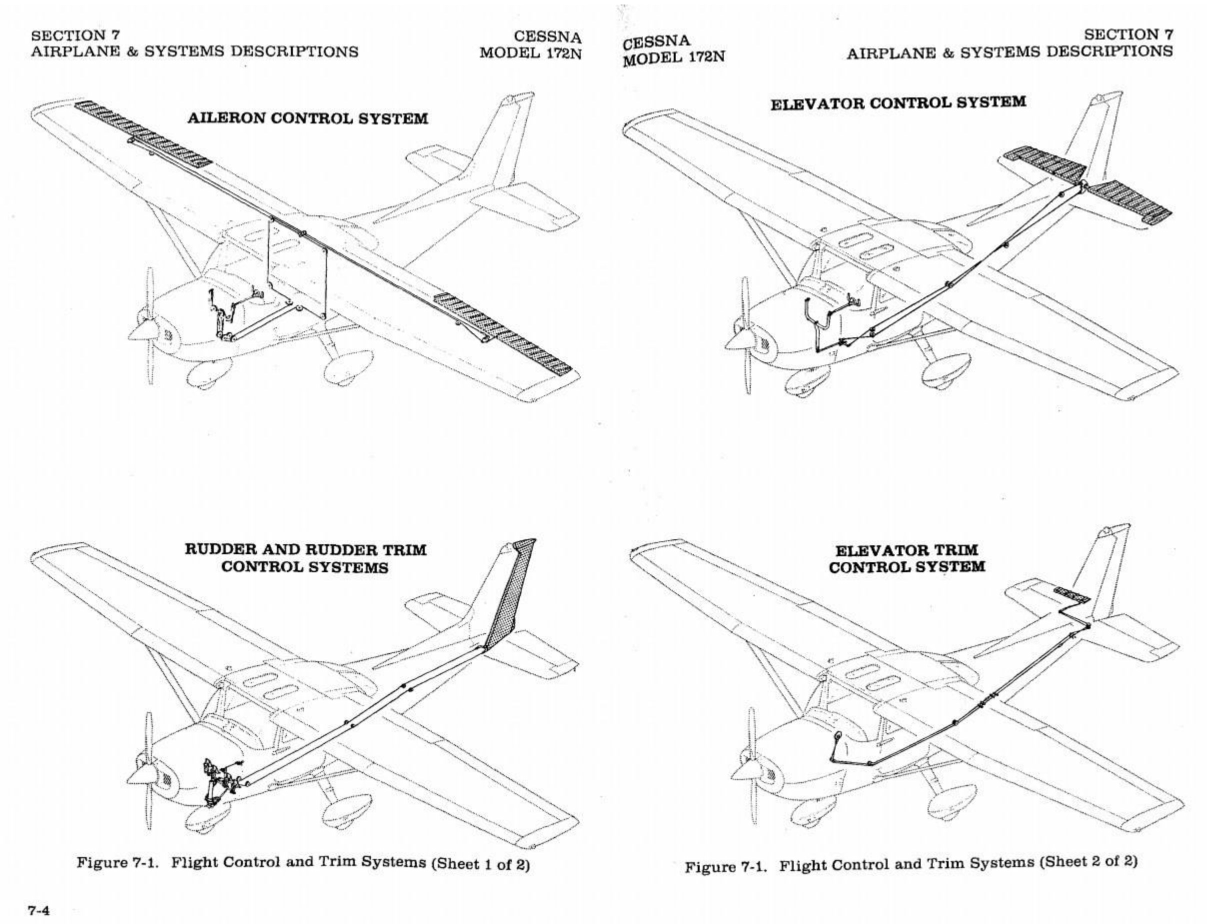

Figure 1: Cessna 172N control system from Pilot operating handbook (Unknown, 1977)

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 by **(Hab-1)**. 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 (Nicolin & Nicolin, 2019). The system offers the most benefits for military and large aircraft. However, the emergence of Urban Air Mobility (UAM) aircraft concepts has made the spread of fly-by-wire systems among small aircraft increasingly relevant.

1.1 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.

1.1.1 Situational awareness

Situational awareness, as described by (Endsley, 1988, 2000), 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, 2002) 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 (Schutte & Trujillo, 1996).

1.1.2 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., 1991), 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, 2001) 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 (Wierwille & Connor, 1983).

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.

1.1.3 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" (Schutte & Trujillo, 1996). 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, 1981) 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.

1.2 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.

1.2.1 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 (Müller, 2020):

- 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.

1.2.2 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 (Müller, 2020).

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 (Wolfe et al., 2015). The mentioned results are average values. The real value depends on many aspects such as age or cue intensity.

1.2.3 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 (Kosinski, 2008; Niemi, 1981). The reaction time significantly increases when any decision is required.

1.3 Bio-inspired aircraft control

This paper **(Hab-1)** was the first work of the authors in the field of pilot-aircraft interaction, leading to 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.

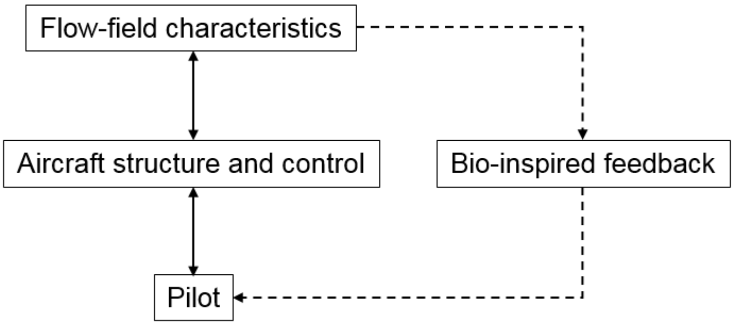

Figure 2: Bio-inspired feedback schema **(Hab-1)**

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.

1.4 Research goals

In view of the literature search presented in **(Hab-1)**, 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.

2 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.

2.1 Directional vibrotactile feedback

We designed and tested the first device 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 **(Hab-2)**. 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.

2.2 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 **(Hab-4)**. 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 **(Hab-3)** 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 **(Hab-3)**

2.2.1 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 **(Hab-9)**, 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).

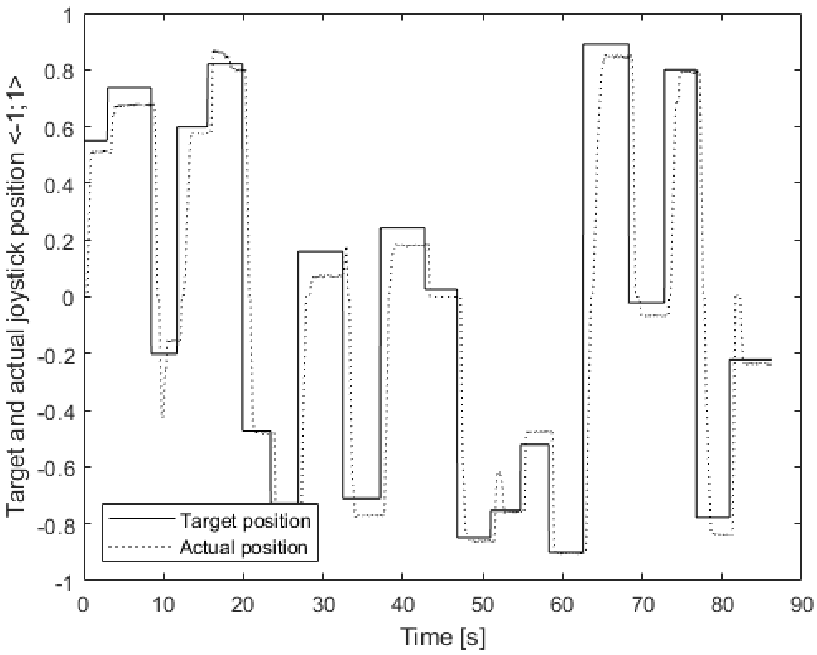

Figure 4: Sample recording of the guidance to randomly generated forward to backward joystick position tested in Task 1 ***(Hab-9)***

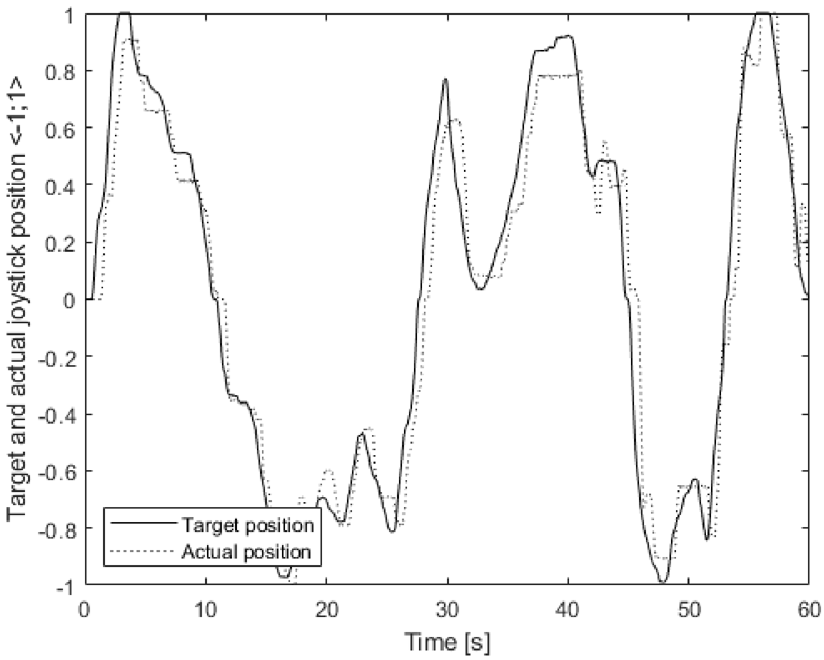

Figure 5: Sample recording of the guidance to continuously changed forward to backward joystick position tested in Task 2 ***(Hab-9)***

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 (Stanley & Kuchenbecker, 2012), (Rognon et al., 2019).

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 (Craig & Evans, 1987), 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 **(Hab-9)**.

3 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 (**Hab-6**), CZ 33800 U1_2020 (**Hab-7**). 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.

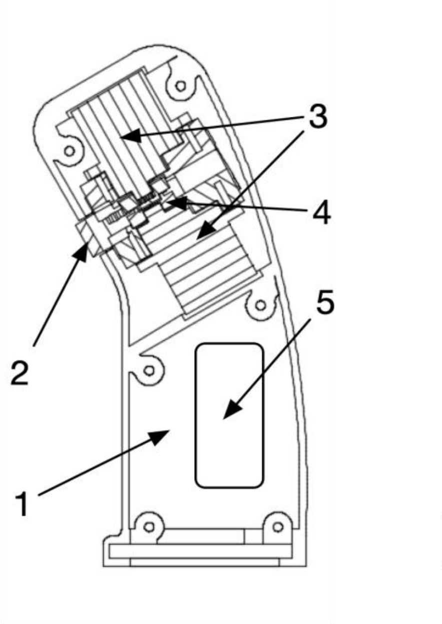

*Figure 6: Joystick handle with two servos powering the sliding element **(Hab-6)***

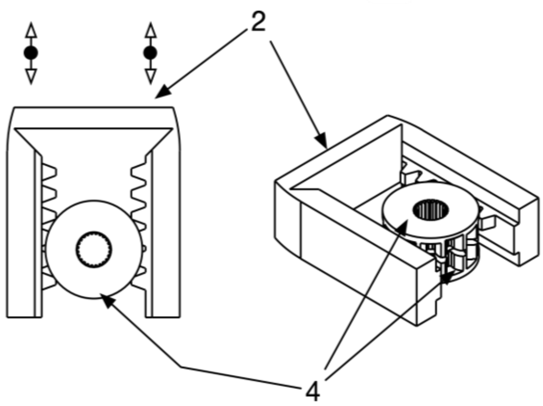

*Figure 7: Sliding element gearing mechanism which allows symmetrical and asymmetrical movement **(Hab-6)***

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 (Vavra, 1984), 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 (Milgram, 2007). 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).

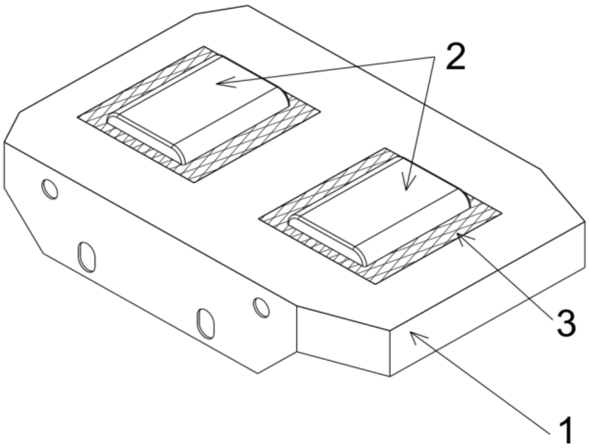

Figure 8 A sample solution of flat-type pedal with vibration elements ***(Hab-7)***

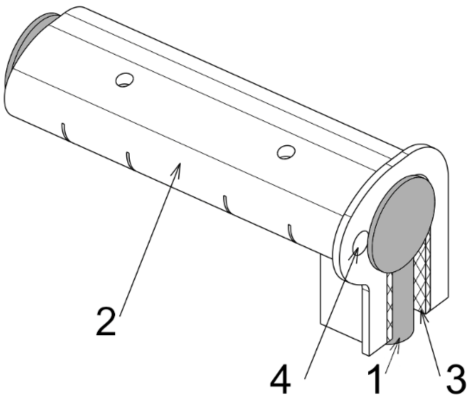

Figure 9: A sample solution of rod-type pedal with vibration motors position (Hab-7)

4 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 **(Hab-5)**, despite the order of the tests. Later, an extended version of the paper was published **(Hab-8)**, which included a description of the flight simulator test and its results. In this thesis, the chronological order of events is followed.

4.1 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 ***(Hab-8)***

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.

4.2 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.

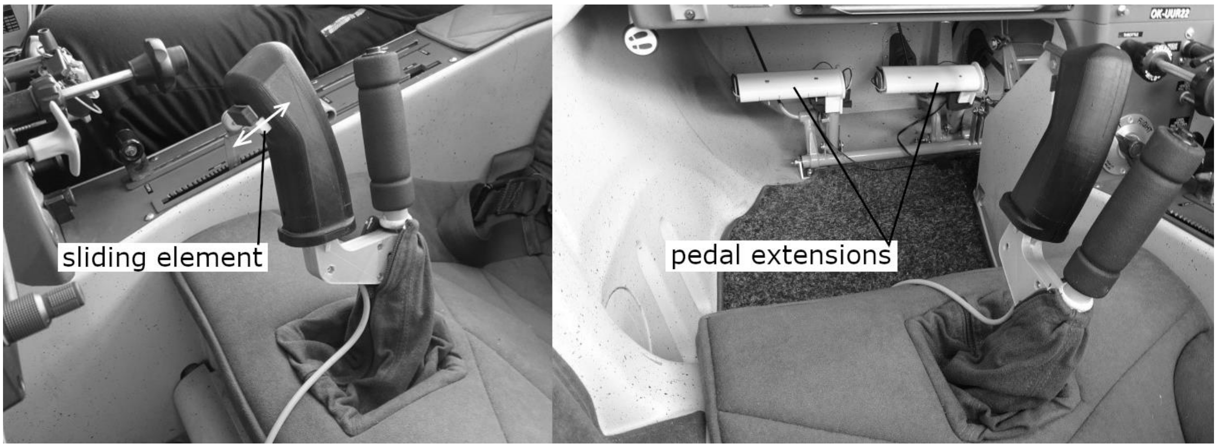

Figure 11: Sliding element and vibration pedals mounted in the aircraft cockpit ***(Hab-8)***

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.

5 Learning effect measurement

The demand for learning speed in using haptic feedback led to the conduction of a subsequent experiment **(Hab-9)**. 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.

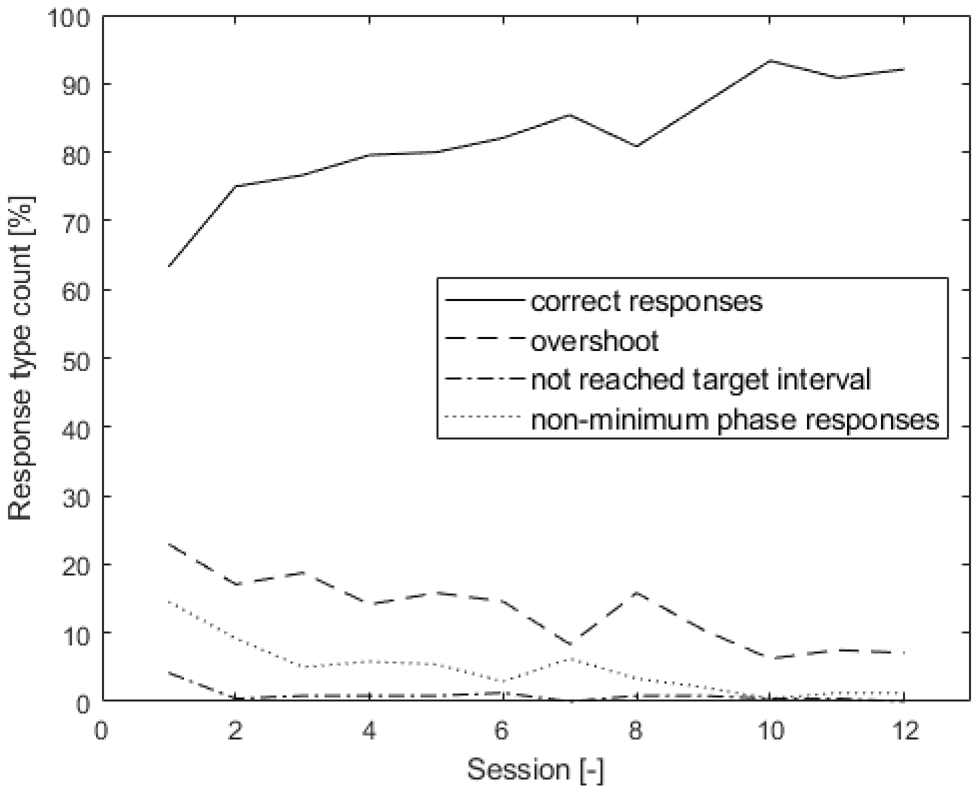

*Figure 12: Count of all participants' response characteristics (**Hab-9**)*

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.

5.1 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., 2018) 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., 2021) 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 (Molnar & Gair, 2015), 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 (De Stigter et al., 2007) and (Nieuwenhuizen & Bülthoff, 2014). (Voudouris & Fiehler, 2017) 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., 2001) 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 Human centred design

The last paper **(Hab-10)** attached to the thesis 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, 1996). 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.

Usability defines (Nielsen, 2012) 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 **(Hab-10)** 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.

CONCLUSIONS AND FUTURE WORK

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 Chapter1.4.:

- 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 devices for rudder pedals and aircraft control sticks capable of providing haptic feedback to pilots. These devices were then experimentally tested using flight simulators and flight tests. A major outcome of the work is the comparison between vibration and sliding element methods for guidance tasks. The sliding element method was found to significantly outperform vibrations in this regard. However, vibrations proved invaluable in a warning capacity. Experiments revealed the need for individualized settings and training in the use of haptic feedback. That opens a demand for an adaptive control system to achieve the best performance with any single pilot or operator. The developed hardware has been successfully employed, providing information about the Angle of Attack (AoA) and Angle of Sideslip (AoS) to flight simulator and aircraft pilots.

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 (UAM) 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	
UAM	Urban Air Mobility	
VLA	Very Light Aeroplanes	

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Aircraft Engineering and Aerospace Technology

Bio-inspired aircraft control

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Bio-inspired aircraft control

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Abstract

Purpose – This paper aims to present a state-of-the-art review in various fields of interest, leading to a new concept of bio-inspired control of small aircraft. The main goal is to improve controllability and safety in flying at low speeds.

Design/methodology/approach – The review part of the paper gives an overview of artificial and natural flow sensors and haptic feedback actuators and applications. This background leads to a discussion part where the topics are synthesized and the trend in control of small aircraft is estimated.

Findings – The gap in recent aircraft control is identified in the pilot–aircraft interaction. A pilot's sensory load is discussed and several recommendations for improved control system architecture are laid out in the paper.

Practical implications – The paper points out an opportunity for a following research of suggested bio-inspired aircraft control. The control is based on the artificial feeling of aerodynamic forces acting on a wing by means of haptic feedback.

Originality/value – The paper merges two research fields – aircraft control and human–machine interaction. This combination reveals new possibilities of aircraft control.

Keyword Aircraft control

Paper type Literature review

Nomenclature

Definitions, acronyms and abbreviations

A-PiMOD = Applying pilot models for safety aircraft;
ACROSS = Advanced cockpit for reduction of stress and workload;
ALICIA = All condition operations and innovative cockpit infrastructure;
AoA = Angle of attack;
AoS = Angle of Sideslip;
CTA = Constant-temperature anemometry;
EASA = European Aviation Safety Agency;
EAP = Electro-active polymers;
ERM = Eccentric rotating unbalanced mass;
GA = General aviation;
HMI = Human–machine interaction;
LOCI = Loss of control in flight;
LRA = Linear resonant actuator;
MEMS = Micro-electro-mechanical systems
NTSB = National Transportation Safety Board;
SA = Situational awareness;
SAW = Surface Acoustic Waves; and
VFR = Visual flight rules.

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Aircraft Engineering and Aerospace Technology
© Emerald Publishing Limited [ISSN 1748-8842]
[DOI 10.1108/AEAT-01-2017-0020]

Introduction

Aircraft control has changed radically because of electronic systems boom in recent decades. Most aircraft are equipped with autopilots, which help to reduce pilot's workload. The interaction between a pilot and autopilot is a key safety task (Degani and Heymann, 2000), and all complex systems in aircraft are designed with human-centric ergonomics (Sanjog *et al.*, 2015). The paper is focused on small aircraft without autopilots. These aircraft are used mostly for sport and leisure time flying. The control system has remained fundamentally the same since the beginning of powered flying. This system is

The research leading to these results has received funding partially from the MEYS under the National Sustainability Programme I (Project LO1202). It has also been partially supported by the Technology Agency of the Czech Republic under the research program TE01020415 (V3C – Visual Computing Competence Center) and by the project Navigation of handicapped people funded by grant no. SGS16/236/OHK3/3T/13 (FIS 161 – 1611663C000).

Received 11 January 2017
Revised 23 November 2017
2 January 2018
30 January 2018
3 April 2018
Accepted 3 April 2018

well tested but retains the most dangerous element, which is the human factor (Li *et al.*, 2001; Dekker, 2002).

What is the motivation to change something as well-established as an aircraft control? The inspiration for an innovative flight control system comes from nature. Birds are capable of perfect motion in the air because they can feel the air-flow around their wings. This advantage is most prominent at low airspeeds, near the stall condition, where the birds are able to safely exploit the maximum lift generated by their wings. This benefit can theoretically be achieved on aircraft and a pilot by artificial haptic feedback as shown in Figure 1. A bio-inspired feedback is supposed to mediate speed, angle of attack and sideslip (AoA and AoS) and possible flow separation by a haptic modality to a pilot.

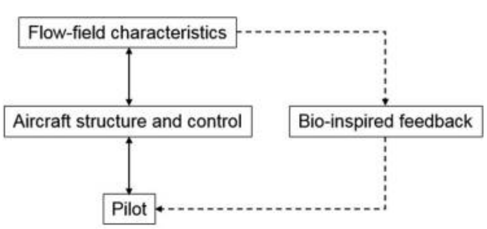
The second motivation to improve aircraft control stems from the flight safety reports. EASA annual report (EASA, 2014) points out a trend saying that loss of control in flight (LOCI) is the most frequent reason of fatal aircraft accidents in general aviation (GA) below maximal take-off weight of 2,500 kg. EASA states that on average, 153 fatal accidents with 255 fatalities per year happened from 2009 to 2013. About 33 per cent were caused by LOCI. NTSB in the USA (NTSB, 2012) gives an even higher number, approximately 100 fatal accidents a year caused by LOCI, which is about 40 per cent of all fatal accidents. Preventing LOCI is on the NTSB Most Wanted List 2015 (NTSB, 2015), and EASA is heading to change regulations for pilot training (EASA, 2015). The goal of the new bio-inspired control system is to decrease the LOCI-induced accident count. LOCI is not only an issue for small aircraft. The flight accident of A330 (Flight AF447) in 2009 was finally caused by LOCI after interplay of unfortunate circumstances.

The scope of the paper is a review of technologies that have a potential to improve control of small aircraft. The review part leads to a discussion, where full-extent and realistic scenarios of bio-inspired aircraft control are presented. The architecture of aircraft control is supposed to be human-centered; therefore, the whole control loop from sensors to perception psychology is considered in the review part. The discussion chapter follows the state of the art. Recommendations for sensors and actuators and pilot's modalities loading are specified there. A research roadmap section proposes some steps for future work.

State-of-the-art review

This section summarizes related prior work. The focus is put on conventional and natural air flow sensors at first. Haptics description as an important modality in aircraft control follows. Vibrotactile actuators and its applications in warning, control and guidance domains are presented. Recent projects dealing with pilot–aircraft interaction are described. Perception psychology is introduced at the end.

Figure 1 Traditional aircraft control way and its bio-inspired extension



Conventional flow sensors

A number of sensors can be deployed to understand flow conditions over an aircraft wing. Historically, vanes have been among the first to be used. They detect AoA, which is correlated to the flow regime around the wing. Certain commercial anti-stall systems feature this approach (2014b) among others. These sensors are simple yet delicate, rendering them less appropriate for operational deployment. To overcome the aforementioned hurdle, dynamic pressure probes have been used widely for wind tunnel experiments and in-flight investigations (Hahn and Schwarz, 2008). This type of sensor is pivotal for several commercial anti-stall systems (2014a, 2013b) among others. Another sensor used among stall avoidance systems is a latch reacting to the stagnation point position (2015b). Constant-temperature anemometry (CTA)-based systems have been used for more precise measurement of the stagnation point location in many research projects (Mangalam and Moes, 2004).

However, all the sensors provide only an indirect indication of the flow over the wing. To obtain a direct reading of the pressure distribution and hence flow separation extent, pressure taps have been used as the reference tool for decades. Being used predominantly for wind tunnel measurements (Corke *et al.*, 2011) and some in-flight experiments (Powers and Webb, 1997), they are not well suited for operational deployment due to blockage sensitivity, limited resolution and dynamic response. Arrays of micro-electro-mechanical systems (MEMS)-based sensors are a viable candidate to be used instead (Holland *et al.*, 2001; Kim *et al.*, 2000). CTA MEMS hot-film sensors (Que *et al.*, 2011; Zhu *et al.*, 2009) have been developed and are used extensively, e.g. for laminar-turbulent transition in-flight monitoring (Marshall, 2000). Apart from knowing the transition/separation position, AoA and other parameters can be obtained from these sensors indirectly (Que and Zhu, 2012). Calorimetric MEMS sensors (Obermeier *et al.*, 2008; Sturm *et al.*, 2012) present a viable alternative to the CTA approach. MEMS shear-stress sensors are deployed (Xu *et al.*, 2003) among other approaches (for review, see Löfdahl and Gad-el-Hak, 1999). Relevant commercial MEMS-based pressure sensors are readily available (Meggitt, 2014). Lately, integrated MEMS sensor-actuator systems (Francioso *et al.*, 2015) are being successfully tested. MEMS microphone arrays might become a promising separation detector in the future. An alternative to MEMS, piezoelectric sensors exploiting surface acoustic waves (SAW) are being increasingly used among a number of industries (2015c). They are passive components interrogated wirelessly by a remote transceiver. This attractive characteristic implies a straightforward integration. Although this technology has been known for decades (Reeder and Cullen, 1976), the real applications in transportation industry started to emerge later (Drafts, 2001).

Thin tactile sensors based on pressure-sensitive conductive rubber (Obara *et al.*, 1985) have been used for medical research (Volf *et al.*, 1997) and might become available for aviation industry once adapted to the pressure ranges experienced on the surface of a GA aircraft. Analogically, resistive thin-film technology has found several applications (2016b). Although suffering from limited accuracy, significant hysteresis, creep and long-term instability (Ashruf, 2002), it provides real-time full-field data on the pressure distribution. Capacitive thin-film technology might possibly be a better alternative for flow separation mapping due to better long-term stability, increased repeatability of the measurements and sufficient resolution down to 10 Pa. A novel thin-film sensor featuring optical fiber Bragg grating principle has been demonstrated recently (2015a); however, it has not been commercialized yet. A review of conventional sensors has been performed by Mohamed *et al.* (2014a). The same author evaluated bio-inspired sensor technology with a goal to improve micro air vehicle flight in turbulence (Mohamed *et al.*, 2014b).

Natural flow sensors

An insect is naturally equipped with many sensilla hairs. These sensilla receptors differ by its architecture and supply a nervous system by various inputs (Keil and Steinbrecht, 1984; Keil, 1997; Shimozawa and Kanou, 1984a, 1984b). The flow control sensilla can detect small-amplitude, low-frequency air disturbances (Levin and Miller, 1996). A conceptual air flow sensor was modeled and demonstrated by Ozaki *et al.* (2000). Cricket-inspired artificial sensors were designed by Dijkstra *et al.* (2005); Krijnen *et al.* (2007) and Chen *et al.* (2007). Sensilla hairs cover an insect's body usually in thousands of pieces. This rich sensor control system with numerous feedback loops is described by Zbikowski (2004). The benefit of high-density hairs in comparison to a single hair is discussed by Casas *et al.* (2010). Another research was focused on vibration receptive sensilla on the wing of a silkworm moth (Ai *et al.*, 2010). Sensilla optimal frequency and physical limits in vibration frequency were evaluated by Bathellier *et al.* (2011). A comparison of cricket sensilla with MEMS hairs was done by Droogendijk *et al.* (2014).

The only flying mammal is a bat. At first sight, its wing appears hairless, but microscopically small hairs can be found by detailed inspection. The function of these hairs is to provide aerodynamic feedback for flight control (Sterbing-D'Angelo and Moss, 2014). Birds' skin is covered by feathers which works in a similar way as sensilla in the insect case. Several structural types of feathers were described by Stettenheim (2000). Feathers are attached to the skin in follicles, which are surrounded by mechanoreceptors with various response characteristics (Hörster, 1990a, 1990b). Birds use mechanoreceptors on their wings for air-flow characteristics indication. The study (Brown and Fedde, 1993) has showed a correlation between wind speed and feather vibrations, also correlating to a signal from mechanoreceptors. Barn owl and pigeon wings and feathers have been described by Bachmann (2010) in detail.

Haptic feedback

Animals detect flow characteristics in a haptic way. Therefore, usage of haptic feedback in aviation is reviewed in the following section. The most important modality in aviation is vision (Gillingham and Previc, 1993). Focal and ambient vision are important for object recognition and spatial orientation. However, haptic sense mediates an important invisible interaction between the pilot and an aircraft. Most common examples of haptic sense in small aircraft are speed estimation by the resistance and shaking of controls when a stall is approaching and turbulent flow is hitting aircraft's control surfaces. The reaction of an aircraft on a gust or control input is perceived through pilot's seat. In case of modern aircraft equipped with powered controls or with fly-by-wire control system, there is typically a stick shaker installed. This device simulates haptic feedback of forthcoming stall condition by similar stick shaking as in case of aircraft with directly connected control surfaces. Touch is also used to determine the position of various controls. For instance, it is usually possible to assess the position of flaps, gear handle, etc. only by touch and control position regarding pilot position.

Haptic interaction also has several limitations. According to Craig and Evans (1987), a person continually adapts to a constant tactile input. Moreover, a perception of multiple tactile inputs can induce specific sensations. Two inputs that are near to each other can be sensed as one input (Verrillo, 1965). The intensity of one input can affect the perceived intensity of other tactile inputs at the same moment (Hahn, 1966).

Vibrotactile actuators

Standard haptic feedback is provided by vibration actuators. Common types of vibration actuators are eccentric rotating unbalanced mass (ERM) and a linear resonant actuator (LRA) with a spring powered by electromagnetic force (Choi and Kuchenbecker, 2013). ERM is a simple device with off-centric mass powered by a motor. The actuators are cheap, easy to control and able to produce strong vibrations. Vibration frequency and intensity are coupled. Disadvantages are slow reaction time (around 30-50 ms) and low fidelity of sensations. LRA is slightly faster with 20-30 ms response time. Power drain is half-valued and dimensions are smaller in comparison to ERM. The frequency of vibration is limited to a single resonant frequency. Vibration strength is medium. Another option for haptic feedback devices is a piezo actuator (2016a). A variable frequency with fast response up to 5 ms produces high fidelity feedback. Downsides of piezo actuators are costs and more complex electronic control in comparison to ERM and LRA. A similar solution to piezo actuators is electro-active polymers (EAPs). The main practical difference of EAP actuators is that they need high voltage power. A possible alternative to the vibration motors are servo motors. The haptic feedback would be mediated by morphing the shape of a stick handle instead of vibrations.

Warning and guidance applications

Usually, non-directional tactile displays are used in warning applications. A stick shaker is commonly used to warn a pilot about approaching stall conditions. One design of a stick shaker was patented as early as 1951 (Greene, 1951). The stall warning system is fed by a variety of AoA sensing devices. Human–machine interaction (HMI) is becoming more important in recent decades. (Sklar and Sarter, 1999) demonstrated that tactile feedback is more effective than visual in catching human attention. A tactile warning system has been studied in car driving research. Experiments with drive simulator with haptic feedback were performed by Ho *et al.* (2005); Spence and Ho (2008) and Meng *et al.* (2014). The result of the research is a faster reaction of the driver to an unexpected situation. Multimodal feedback, a combination of tactile and visual and auditory feedback, is discussed by Haas and Van Erp (2014). Usage of multimodal warnings demands balanced signals coming from different senses which are proportional to warning importance and urgency.

Directional tactile displays offer more possibilities than the warning function. Tactile vest (Jones *et al.*, 2004) and waist belt (Van Erp *et al.*, 2005; Weber *et al.*, 2011) offer multielement tactile feedback. van Erp (2007) even studied a tactile display that consists of 64 vibrotactile elements with a goal to help a pilot with guidance and control tasks. He also found that localized vibration on a pilot's body was easily coupled to spatial information like direction to a waypoint or a threat. A wrist device for vibrotactile feedback was studied for various reasons. (Kammoun *et al.*, 2012) studied vibrotactile feedback assistance for blind people. HMI, telepresence and augmented reality are other applications studied in the frame of haptics (Stanley and Kuchenbecker, 2012; Scheggi *et al.*, 2012; Schönauer *et al.*, 2012). A vibrotactile device alerting a pilot about an aircraft attitude is presented by Cardin *et al.* (2006). The effect of haptics and automation on pilot performance and control behavior has been tested and evaluated by Olivari *et al.* (2014) recently. (Nieuwenhuizen and Bülthoff, 2014) focused the haptic feedback into personal aerial vehicle control by a highway in the sky display with a goal to create an easy to use control interface for non-expert pilots.

Aircraft control applications

There are other HMI applications in aircraft control domain. Patent (Vavra, 1984) is a similar device to the stick shaker mentioned in the section Warning applications. The device alerts an aircraft pilot to uncoordinated turn condition. Sarter and Woods (1992, 1994) studied pilot–aircraft interaction. The interaction affected flight quality and the human role in aircraft control significantly because of the rapid automation of aircraft during the 1990s. Boy (1999) referred to the importance of cognitive function analysis of human-computer-aircraft systems. Preliminary experimental evaluation of haptic feedback applied to remotely piloted vehicles was presented by Alaimo *et al.* (2010). The last application imitates nature with the purpose of solving human tasks. Blower and Wickenheiser (2010) introduced a concept which enhances aircraft stability and maneuverability during flight. The design consists of feather-like components installed on a wing surface. These structures act as sensors, actuators and load bearing at the same time.

Recent projects

This section describes recent projects which touch the topic of bio-inspired aircraft control and HMI and highlight some publications created within the projects. Project ALICIA (2009) aims to increase time efficiency within the future air transport systems. A key objective is to deliver extensible solutions that can be applied to many aircraft types. This entails a new cockpit infrastructure capable of delivering enhanced situational awareness to the crew whilst simultaneously reducing crew workload and improving overall aircraft safety. The myCopter (2011) project aims at personal aerial vehicles to be used by the public within the context of such a transport system. Mentioned publications (Nieuwenhuizen and Bülthoff, 2014; Olivari *et al.*, 2014) were produced within the MyCopter project. ACROSS project (2012) assess workload volume and stress of pilots. ACROSS consortium develops new cockpit applications and human–machine interfaces with a goal of reducing crew workload and improving the safety of two-pilot operations. A-PiMod project (2013a) contributes to the improved human-centered design of future aircraft cockpits. The project evaluates whether during a flight the crew and/or the automation system must act to guarantee that the overall human-automation system remains within a safe state. This is achieved by a real-time risk assessment and a real-time crew model. A new cockpit architecture with a potential to improve the safety of future aircraft was published by Javaux *et al.* (2015).

Perception psychology

Perception psychology is the last direction missing in the review part. Bio-inspired idea of aircraft control aims not only to better controllability but also to decrease of pilot's mental workload. Human-centered aircraft control requires being designed with taking account of perception psychology and mental workload.

Wickens (2008) focuses on mental workload and divided attention. While an operator performs multiple tasks at the same time, the ability to successfully perform simultaneous tasks depend on various factors. Wickens introduces a term difficulty insensitivity, which corresponds to a situation when an increase of the difficulty of one task does not degrade the performance of a concurrent task. He presents a model, where difficulty insensitivity depends on three dimensions: modalities (e.g. auditory or visual), codes of processing (verbal, spatial) and stages of processing (perceptual, cognitive). This model corresponds to the physiological structure of human nervous system, where different "resources" correspond to units of dimension in the model mentioned. For example, auditory perception uses different resources than visual perception does. Wickens concludes that tasks with a higher degree of resource overlap suffer from greater dual task decrements. He suggests using an additional modality, e.g. tactile input.

In aviation, various illusions can interfere with human perception (Gillingham and Previc, 1993). Most notably, visual illusions and spatial illusions can lead to pilot disorientation with possibly severe consequences. An additional modality that is used for the representation of information vital for safe flight operation could lead to faster recovery from illusions.

According to Endsley (1988), situational awareness (SA) refers to "the perception of the elements in the environment within a volume of time and space. The comprehension of their meaning and projection of the near future." It involves perceiving critical factors in the environment (Level 1 SA), understanding what those factors mean (Level 2 SA) and understanding what will happen in the near future (Level 3 SA). For a successful flight operation, it is necessary to create and maintain good situational awareness. Good perception of external factors is a vital precondition for such a process.

Discussion

Bio-inspired aircraft control modifications are proposed in the following chapter. A full-extent way of bio-inspired aircraft control is presented at first. Realistic draft of current aircraft control improvement is introduced then. The next part proposes a road-map for experimental research and future work.

Full-extent bio-inspired way of aircraft control

Birds and flying insects are equipped with visual, air-flow, inertial and wing loading sensors. These sensor inputs are processed in the neural system. Therefore, animals fly as naturally as people walk. The idea of bio-inspired aircraft control aims to provide an ideal pilot–aircraft interaction. The interaction would provide characteristics of flow around aircraft to a pilot by intuitive way that does not require any special pilot's attention. Pilots should feel AoA, AoS, dynamic pressure and gradual flow separation in the same way as animals. This interaction would be mediated by tactile actuators in controls (stick and pedals) and a seat, eventually by actuators attached to pilot's body. Such system would provide best control performance of aircraft piloted by a human pilot. This full-extent bio-inspired way of aircraft control is connected to some disadvantages on the other side. Development of such system would cost too much to be suitable for manufacturers of small aircraft nowadays. The second disadvantage would be a need of a completely new way of flying control and its learning. Therefore, a realistic draft of current aircraft control improvement is discussed more deeply in the following section.

Realistic scenario

"Realistic scenario" is called bio-inspired improvement of aircraft control system based on current aircraft control equipped with additional haptic feedback. The feedback system will consist of a sensor part, a control unit and an actuators part. The actuators part is planned as an extension to control stick and pedals with vibration motors and servos. These motors will be controlled by a control unit which collects data from the sensor part. The control unit will evaluate optimal and dangerous flying regimes. The realistic scenario is expected to decrease the mental workload of a pilot and reduce response time in case of approaching dangerous regime. The control way of an aircraft will remain the same at the same time.

Sensors and actuators requirements

Animals feel the air-flow perfectly by using a high number of sensors giving them information about the dynamic pressure, the direction of incoming flow and possible flow separation. Natural flow sensors are represented by sensilla hairs among insects and feathers among birds. The artificial sense hair is under development (Dijkstra *et al.*, 2005; Droogendijk *et al.*, 2014), but a real-world application is still to be demonstrated. Full-extent bio-inspired way of aircraft control is based on knowledge of pressure distribution on wing and tail unit. Therefore, thin films spread on an aircraft could be a solution. A conventional sensors configuration for the realistic scenario of bio-inspired control leads to AoA and AoS vanes with airspeed indication. Such configuration would provide good flow characteristics even in the nonlinear region of lift curve. The main disadvantage of AoA and AoS vanes is that they stick up of aircraft surface and can be damaged by ground operations. Benefits of this sensor configuration are good prize, low weight and verified technology in comparison to sensors measuring distribution of flow characteristics over wing and tail unit.

All described actuator types can be found in real applications. The main requirements for actuators in aircraft control haptic feedback will be size, reaction time and reliability. ERM actuators are large and slow in comparison the others. EAP and piezo actuators are fastest but require complex electronic control system. EAP sensors are not suitable from safety reason because of high voltage supply need. LRA seems to be the best option with good size, reaction time and low voltage simple control. Extensions on control stick and pedals are expected in the realistic scenario of bio-inspired aircraft control. Such extension could be installed on current aircraft controls. The definite choice of actuators will be done later in the framework of the design process of the extension prototypes. The essential requirement for the stick extension prototype will be a haptic information presentation method that does not depend on the way of handle holding in a pilot's palm.

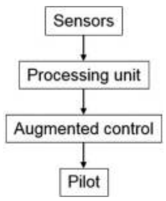
Pilot's modalities loading: The best result would be reached if a pilot's brain could receive inputs from all mentioned modalities in the same way as animals. Information should be presented in a natural way, and the method should prevent sensory overload. This idea of connecting a human nervous system to all sensors is technologically unrealistic yet. Therefore, partial suggestions for bio-inspired control are defined in the following points:

- The visual modality is overloaded in the traditional control system concept. It is not possible to check all important flight indicators at the same time, especially in an emergency situation. The recommendation for visual modality is as follows: the sight should be dedicated to navigation and sense and avoid roles. The numbers of parameters checked by eyes should be limited. Variables that do not change too often, such as flap deflection, fuel state, throttle or altitude, can be monitored by sight.
- The touch is already an important sense in traditional aircraft control concept. The touch modality is an encompassing term including pressure, vibration and balance sensing. Control surfaces provide the pilot with a force feedback. Good balance feeling enables the pilot to fly a coordinated turn. The aircraft approaching stall should also warn the pilot with vibrations. The recommendation for bio-inspired aircraft control system is to transfer additional inputs to touch modality. Magnitudes of speed or AoA and vertical speed should be mediated to the pilot by touch. The artificial feeling of air-flow and its separation over the wing would bring a significant improvement of safety under the most dangerous flight phases. All these inputs are expected to make aircraft control faster and more intuitive.
- The hearing modality is commonly used for communication and warning signals. It will be unchanged in the bio-inspired aircraft control.

Research roadmap

An initial step of the future research is the design and implementation of the integration method from the perspective of HMI. Figure 2 depicts the information processing of the bio-

Figure 2 Bio-inspired haptic feedback



inspired haptic feedback system. Firstly, data collected from various sensors are processed in a dedicated unit. The information about AoA, AoS and flight speed is then continually presented to the pilot by morphing the shape of the control stick and vibrating the stick and the pedals using actuators. Vibration motors are going to be used to provide warning information about approaching stall conditions (critical AoA) or to guide to optimal regimes (for example a turn with zero AoS). Unlike the case of a conventional stick shaker, multiple vibration motors will provide more complex information about flow-field characteristics.

Proposed research steps

Following steps are going to be performed to prove benefits of bio-inspired improvement of aircraft control. Reactions on directional vibrations applied on control stick are going to be analyzed at first. The first experiment is supposed to reveal whether a pilot can distinguish the direction of vibrations and react by a demanded control input. Such experiment could be done just with a modified joystick. Morphing shape of stick handle will be tested to prove an idea that pilot can perceive continuous information by the touch modality. The second step will follow satisfying results of the first experiments. Functional extensions for control stick and pedals will be designed and tested on a flight simulator. Haptic feedback function will be connected to flight data taken from flight simulator software. Control function for haptic feedback needs to be defined. A pilot will undergo quick training with the haptic feedback to get best benefits of aircraft control in reaction time and pilot workload reduction. The last step will be flight, a test of the suggested bio-inspired improvement of aircraft control.

Research goal and comparison to current technologies

Reduction of pilot workload and improvement of aircraft control are the primary goals of the proposed research. Both goals are expected to gain by improvement of aircraft-pilot interaction. Variables such as speed, AoA and AoS perceived by touch will be permanently felt without the need of watching any instruments. It has a potential to make aircraft control more intuitive and to support prevention from approaching dangerous regimes. Warning anti-stall systems have a similar function. These systems warn when a stall is approaching without any ambition of aircraft control improvement or pilot workload reduction. Another similar current technology is an autopilot. It can decrease pilot workload and improve aircraft control. There are two arguments against autopilot usage in small aircraft. The first is a high price of an autopilot. The second is the fact that pilots want to control small aircraft by themselves. The system suggested in the realistic scenario is expected to be cheaper than an autopilot because it does not contain actuators in aircraft control system, except a control stick and pedals. It also keeps the control of the aircraft in pilot's hands. Therefore, bio-inspired improvement of aircraft control is expected to have an ambition to help pilot and make flying easier and safer.

Conclusion

The scope of the paper is a literature review of technologies with a potential to make a control of small aircraft better. The literature search consists of flow sensors, vibrotactile actuators, warning and guidance applications and recent research projects. Basics of HMI are laid out with a goal to specify the requirements on the bio-inspired improvement of aircraft control from the pilot perspective. Two scenarios of bio-inspired modification of aircraft control are suggested: the full-extent one and realistic one. Future research road map is presented at the end of the paper.

Nature inspiration of suggested control system modifications is based on the mediation of artificial air-flow feeling mediated to a pilot. The full-extent scenario of bio-inspired aircraft control present ideal pilot-aircraft interaction but is out of possibilities for aircraft manufacturers to deal with it. Therefore, realistic scenario is discussed more deeply. It has a potential to improve aircraft controllability and to decrease a pilot's workload. These benefits profit from better utilization of pilot's nervous system connection to the artificial feeling of air-flow mediated by haptic feedback. The general intention is to alleviate the overloaded visual modality and exploit the underused touch modality. Future work is constituted by a real-world implementation of the proposed concept and subsequent comprehensive flight testing.

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New Trends in Civil Aviation – Socha, Hanáková & Lališ (Eds)

Reaction to directional vibrations applied on a joystick

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ABSTRACT: Human factor is the most common reason for aircraft accident. Therefore, an improvement of pilot–aircraft interaction by vibrotactile feedback is a way of increasing the safety of flight. This study focuses on the ability of pilot to distinguish directional vibration of a control stick and react in a specific direction. To investigate the intuitive reaction of a pilot on directional vibration, human–machine experiment was carried out. For the experiment, aircraft control stick was replaced by a joystick. The task involved the reaction to the directional vibrations of segments mounted on the joystick by an intuitive reaction. A hypothesis that a human can distinguish directional vibration of the control stick and react in specific directions was confirmed with an error rate of approximately 5%. The experiment was carried out with a prescribed way of holding the joystick in hand. This fact limits results generalization. Future work aims at designing new feedback hardware and analyzing the influence of different ways of stick holding.

1 INTRODUCTION

Several modalities can be used for interaction while flying an aircraft. The vision is the primary sense used for gathering information (Gillingham & Previc 1993); however, it is already overloaded. In case of VFR flight, the pilot needs to obtain information about aircraft orientation and altitude, in order to avoid collisions. Moreover, flight instruments mostly generate visual information and vision is used for navigation as well.

Audio and speech modalities are used for communications (radio, intercom). In some cases, audio modality is used for providing information about the rate of climb (typically in gliders) and warnings (ground proximity, collision—TCAS, FLARM). Audio modality is also used for warnings that correspond to the Angle of Attack (AoA) state (low speed, stall warning). However, there is no information about either the rate of change or the desired reaction with the control stick.

The haptic sense is important for sensing controls feedback in aviation. A pilot can estimate airspeed from resistance by the controls or feel a stall condition that, in case of most small planes, causes shaking of the controls caused by turbulent flow hitting aircraft's control surfaces. In case of modern aircraft equipped with power steering or with a fly-by-wire control system, a stick shaker is typically installed. This device simulates haptic feedback of forthcoming stall condition by similar stick shaking to aircraft with directly connected control surfaces. These applications of haptic feedback are commonly spread nowadays in aviation. However, the direction of human-centered control of aircraft aims to sophisticate haptic feedback, which is demonstrated by recent research projects and publications mentioned in the following text.

Haptic interaction also has several limitations. According to Craig & Evans (1987), a person continually adapts to a particular constant tactile input. Moreover, the perception of multiple tactile inputs can induce specific sensations. Two inputs that are near to each other can be sensed as one input (Verrillo 1965). The intensity of one input can affect the perceived intensity of other tactile inputs simultaneously (Hahn 1966).

In general, non-directional tactile displays are used for warning applications. A stick shaker is commonly used to warn a pilot about approaching stall conditions. One design of stick shaker was patented as early as 1951 (Greene 1951). Human–computer interaction is becoming more important in the last decades. Sklar & Sarter (1999) demonstrated that tactile feedback is more effective than visual for catching human attention. The tactile warning system has been studied in research related to car driving. Experiments on drive simulator with haptic feedback were performed by Ho, Tan, & Spence (2005); Spence & Ho (2008); and Birrell, Young, & Weldon (2013). The result of the research is a faster reaction of the driver to an unexpected situation. Multimodal feedback, a combination of tactile, visual, and auditory feedback, is discussed by Haas & van Erp (2014), who pointed to demands of balanced signals coming from different senses, which are proportional to warning importance and urgency.

Directional tactile displays offer more possibilities than the warning function. Tactile vest (van Erp et al. 2007) and waist belt (van Erp et al. 2005) were tested as multielement tactile feedback. It was found that localized vibration on the pilot's body was easily coupled to spatial information like direction to a waypoint or a threat. Vibrotactile device alerting a pilot about an aircraft attitude and helping with aircraft stabilization is presented by Cardin, Vexo, & Thalmann (2006). They found that the most significant benefit of haptic feedback was getting pilot's attention, which is a challenge for haptic interface wearability improvement. Experimental comparison of a haptic aid system and automated pilot has been tested and evaluated by Olivari et al. (2014) recently. Pilot control effort decreased and pilot performance was significantly improved with haptic feedback, although it did not achieve the performance of automated pilot.

A control stick was beyond the focus for directional tactile displays research. The reason is a variety of ways of holding a stick in a hand. Perceiving of directional vibration is strongly dependent on these ways of a stick holding. We aimed at the exploration of directional vibrotactile feedback applied to the control stick despite this fact. This study focuses on fundamental possibilities of directional vibration perception, while the influence of a stick holding way will be analyzed in future research. This work is part of a complex project that aims to investigate various ways to gather, process, and represent information regarding AoA. The goal is to develop a method that will contribute to flight safety by improving development and maintain situation awareness regarding AoA and the rate of its change.

2 MATERIALS AND METHODS

The experiment is supposed to examine the human reaction on directional vibration impulses applied on a control stick. Haptic sense is strongly sensitive to input location along a hand. It means that two vibration motors, which are close to each other, could be felt like a single one, especially when placed too close on one finger or in a palm. Therefore, a joystick with four vibration motors oriented in four directions was used along with the prescribed way of holding it in a hand.

The ability to distinguish the direction of vibration was observed, and the preferred reaction direction was evaluated. The results will be taken into account in a design of a new control stick with haptic feedback. Such design is going to be independent on ways of holding the stick in a hand. The primary hypothesis to be evaluated is that a human can distinguish directional vibrations of a control stick and react in specific directions. The direction of reaction will be consistent for an individual. The secondary hypothesis is that interference caused by the fifth vibration motor will decrease the performance of an operator, that is, it will cause a higher error rate on longer reaction times. Furthermore, we will investigate the effect of individual preferred direction of reaction on error rate and reaction times.

2.1 *Study subjects*

We selected 19 participants (2 female) with average age of 36.61 (SD = 7.97, MIN = 26, MAX = 61), of whom only three participants are left-handers and six participants have a pilot license with average number of flying hours of 478 (SD = 405, MIN = 27, MAX = 1200). Nine participants have some experience with a flight simulator (with four of them having a pilot license).

2.2 *Apparatus*

Hardware for the experiment comprised a joystick, five vibration engines, and Arduino MEGA microcontroller. Genius MaxFighter F-16U joystick represented the control stick (see Fig. 1). Joystick

Figure 1. Joystick with vibration motors.

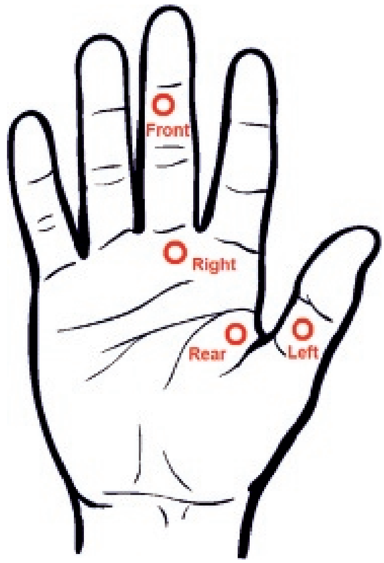

Figure 2. Position of vibration motors in a palm.

potentiometers were connected to the microcontroller for position reading. Four mobile phone vibration engines (LG Optimus Black P970, HTC Desire 626) were used for direction signaling, and one ERC mini vibration motor 4 × 11 mm placed on the top of the joystick was used for simulating interference caused by plane vibrations. Vibration motors were placed on the joystick in four directions—left, right, front, and back (see Fig. 2). Direction vibration motors were fastened by four layers of double-sided tape to insulate the joystick from spreading vibrations in all directions. Control code was run on Arduino MEGA from MATLAB environment.

2.3 *Experimental design*

The experiment was one factor (two levels) within subject design. The independent variable was the presence of *Interference (ON, OFF)*. The main measures were error rate and response time. For statistical evaluation, we used 95% confidence interval.

The experiment was divided into two blocks with 32 vibration inputs. The vibrations were stopped by moving the joystick into one-third of full deflection in any direction. Then, in 2–4 s, a new vibration started. One block was performed with *Interference OFF*, and one block with *Interference ON* by running the fifth vibration motor at the top of the joystick. Half of the participants started with *Interference ON* and the other half with *Interference OFF* to distinguish disturbing from learning effect.

2.4 *Procedure*

Participants were comfortably seated, and the experimental task was introduced to them. Before the experiment started, they filled a pretest questionnaire. The goal presented to the participants was to stop vibrations by moving the joystick to an intuitively chosen direction (It is not a race on time, but an intuitive reaction without any special effort is expected). After both blocks, the subjective evaluation by means of a questionnaire (Likert scale 1–5) was performed.

3 RESULTS

A total of 18 participants chose a direction in response either the same or opposite to that of vibrations. Only one participant could not decide the direction and was changing it during the test. His comment to the experiment was that he was not able to react intuitively and he thought too much about reactions. Data from this participant were removed from our data set processed. The remaining 18 participants chose response directions and followed this decision for the experiment with different success rates. A total of 13 participants selected the same direction as vibrations, and 5 participants selected the opposite direction.

Figure 3a shows the mean error rate measured in the experiment, while the fifth vibration motor simulating interference was turned on or off. A successful reaction can be either in the forward direction (participant moves the joystick in the direction of vibrating motor) or in the reverse direction (participant moves the joystick in the opposite direction).

It seems that the error rate for *Interference ON* (mean = 4.17, 95% CI [2.01; 6.33]) was very similar to that for *Interference OFF* (mean = 5.90, 95% CI [2.58; 9.22]), and the results are largely inconclusive concerning the difference between the test conditions, although in favor of *Interference OFF*.

Figure 3b shows the mean reaction time with and without interference. It seems that the time to react for *Interference ON* (mean = 0.99, 95% CI [0.891; 1.089]) was very similar to that for *Interference OFF* (mean = 0.94, 95% CI [0.843; 1.037]) and the results are largely inconclusive concerning the difference between the test conditions, although in favor of *Interference ON* with longer reaction times.

Figure 3c-f shows the differences in error rate and reaction time for cases where participants decided to react in forward or reverse direction. We show the results for both cases of interference configuration. It seems that the error rate for *Interference OFF forward reaction* (mean = 5.05, 95% CI

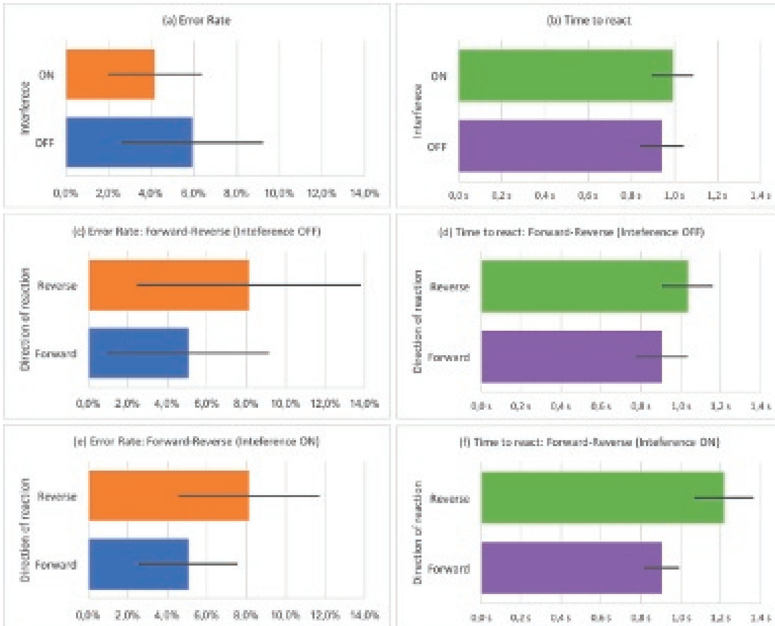

Figure 3. Measurements of the error rate and reaction time.

[0.97; 9.13]) was slightly higher than that for *reverse reaction* (mean = 8.13, 95% CI [2.45; 13.81]), but the results are inconclusive concerning the difference between the test conditions, although in favor of *Reverse reaction* with higher error rate.

It seems that reaction time for *Interference OFF forward reaction* (mean = 0.903, 95% CI [0.773; 1.033]) was slightly longer for *reverse reaction* (mean = 1.034, 95% CI [0:904; 1:164]), but the results are inconclusive concerning the difference between the test conditions, although in favor of *reverse reaction* with longer reaction time.

It seems that the error rate for *Interference ON forward reaction* (mean = 3.13, 95% CI [0.63; 5.63]) was also higher for *reverse reaction* (mean = 6.88, 95% CI [3.31; 10.45]), but the results are inconclusive concerning the difference between the test conditions, although in favor of *reverse reaction* with higher error rate.

Time to react for *Interference ON forward reaction* (mean = 0.903, 95% CI [0.816; 0.990]) was longer for *reverse reaction* (mean = 1.217, 95% CI [1.069; 1.365]), and the results are conclusive concerning the difference between the test conditions, in favor of *reverse reaction* with longer reaction time. We performed a two-sample t-test, with a 99.8% possibility of longer reaction time in case of *reverse reaction*.

The subjective evaluation depicted in Figure 4 indicates that most participants agreed

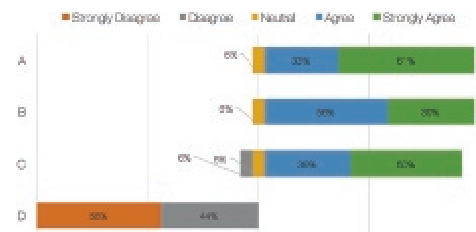

Figure 4. Subjective measures (Likert scores).

that the directional sensation was unambiguous (A). However, the uncertainty was higher in case of *Interference ON* condition (B). For most participants, the decision about the direction of the reaction was easy (C). Most participants also disagreed that the interference influences the direction of their reaction (D). Four out of five participants who reacted in reverse direction commented that close (rear and right) vibration engines perception blended together. However, none of the participants reacting in the forward direction mentioned that.

4 DISCUSSION

The experiment with a joystick was simplified in comparison to real aircraft control because of the prescribed way of the joystick holding in a hand.

Therefore, application of results should be interpreted only by considering this limitation. The primary hypothesis that a human can distinguish directional vibrations of a control stick and react in specific directions was verified with the error rate of approximately 5%. The secondary hypothesis that the interference caused by the fifth vibration motor will decrease the performance of an operator was disapproved. The interference caused by the fifth vibration engine influenced results by neither objective nor subjective evaluation. Slightly better error rate when interference was ON could be a random event or could be caused by the stronger concentration of participants during interference. Four of five participants who reacted in reverse direction commented that close (rear and right) vibration engines perception blended together. They also had a slightly longer response time. These facts could be interpreted by the fact that these participants were thinking more about the reaction. Therefore, forward reaction seems to be a better way for future studies on pilot–aircraft interaction. One participant perceived vibrations as a command, which allowed him to perceive a simple reaction without any hesitation; therefore, it could be a way of instruction how to react in future experiments.

5 CONCLUSION

In this paper, we described the experiment focused on the response of a human to directional vibration impulses of vibration motors attached to a joystick. A total of 18 of the 19 participants chosen a direction for the same or opposite side from vibrations. Better results in error rate and time to react were achieved by 13 participants who react in the forward direction. Five participants who reacted in reverse direction performed slightly slowly with a higher error rate. The primary hypothesis that a human can distinguish directional vibrations of a control stick and react in specific directions was confirmed by the error rate of approximately 5%. Interference caused by the fifth vibration engine has not significantly influenced error rate as well as time to react.

The experiment was carried out with a prescribed way of holding the joystick in a hand. Therefore, future work will lead to a new design of the joystick or control stick handle with directional haptic feedback, which will be independent on ways of holding. Future experiments will be extended to the more complex task including virtual aircraft control. Such experiments are supposed to provide an idea that haptic feedback could decrease the workload of a pilot and improve the quality of aircraft control.

ACKNOWLEDGMENTS

The study was financially supported by the MEYS under the National Sustainability Programme I (Project LO1202) and partially supported by the Technology Agency of the Czech Republic under the research program TE01020415 (V3C—Visual Computing Competence Center).

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Comparison of Joystick guidance methods

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***Abstract*—Human factor represents one of the most common aircraft accident reasons. Therefore, an improvement of pilot-aircraft interaction by tactile feedback could be a way how to make flying safer. The goal of the research is to mediate aerodynamic characteristics of flow-field around the airplane to the pilot and to guide the pilot into avoiding dangerous regimes by the use of haptic feedback. Two guiding methods applied to a joystick are compared in order to improve the pilot-airplane interaction. Vibration motors and a sliding element were built in the joystick. Both methods are compared on two experimental tasks. Reaction time and accuracy of guidance are evaluated for both methods. The results are completed by the subjective opinion of the experiment participants.**

I. Introduction

The control of small aircraft works on the same principle as the control of big airliners, but one aspect is changing recently. Airliners are heading to autonomous flights. Pilot's are not required in airlines because of the airplane's physical control but mostly because of the passenger's thrust and safety [1]. The situation in small aircraft control is different. Sport and leisure time pilots want to keep control of airplanes. Therefore, the human factor is the most common accident reason which leads to a fatal loss of control accidents [2] [3]. Ballistic parachute systems are the best current solution to the loss of control. Galaxy recently stated that 95 lives were saved by their system [4]. This research aims to prevent those situations in which rescue systems are required. The improvement of the pilot-airplane interaction is supposed to make the airplane control more intuitive. A decrease in the pilot workload is expected at the same time [5]. Although the focus on small airplanes, the proposed haptic feedback could be used in any other human-machine interaction application. This research goal could be described as an improvement of the pilot Situational Awareness (SA).

According to Endsley [6], SA refers to "the perception of the elements in the environment within a volume of time and space. The comprehension of their meaning and projection of the near future." It involves perceiving critical factors in the environment (Level 1 SA), understanding what those factors mean (Level 2 SA) and understanding what will happen in the near future (Level 3 SA). For a successful flight operation, it is necessary to create and maintain good SA. Good perception of external factors is a vital precondition for such a process.

In survey [7] Csapo et al. describe the haptic interaction as exploration based on recognition through touching, grasping, or pushing/pulling movements. The authors conclude that the amount of information that can be provided using tactile and haptic feedback is lower than through the visual and auditory senses. However, in the case of aviation, the vision and auditory sense as primary senses are overloaded. The haptic interaction can serve additional information vital for the creation and continuous preservation of SA.

Outcomes of this research can be beneficial for the community of Cognitive Infocommunications (CogInfoCom) [8]. We investigate the possibilities of haptic feedback to improve flight safety in situations critical to attention [9] situations. In the CogInfoCom domain, aviation has been only partially investigated [10].

This paper presents experiments with a haptic feedback device which should mediate flight parameters to the pilot. The Angle of Attack (AoA) is an essential flight parameter in the loss of control occurrence. While birds feel AoA naturally, pilots feel only the response of the airplane structure and the warning systems when approaching a critical regime. The proposed haptic feedback system can mediate flight parameter AoA and optionally angle of sideslip (AoS) to a pilot. Besides the warning function, the system is supposed to guide the pilot to a safe regime when stall threaten. Our experiments compare two different guiding methods: "Vibrations" actuated by vibration motors mounted on a joystick presenting the flight-stick and "Sliding element" actuated by two servo motors embedded into the joystick. Both methods could be used as a stall warning, but the focus is concentrated on the guiding function in this paper.

II. Related Work

Haptic modality significantly relates to spatial orientation. In survey [7], Csapo et al. describe haptic interaction as exploration based on recognition through touching, grasping, or pushing/pulling movements. The convention refers to tactile perception to an interaction where sensations are obtained through the skin, while the haptic perception extends tactile perception with impressions received through the muscles, tendons, and joints. The authors conclude that the amount of information that can be provided using tactile and haptic feedback is lower than through the visual and auditory senses. In [11], Loomis and Lederman present a survey of fundamental research related to the modality of touch. In [7], they stated that touch consists of two distinct senses – the cutaneous sense (tactile perception) and kinesthesis. The haptic perception involves both cutaneous and kinesthetic stimuli. Touch is segmented and sequential, and there are high demands on memory.

The haptic and multimodal interaction has been studied in the last two decades. Van Erp [12] studied a tactile display that consisted of 64 vibrotactile elements with the goal to help the pilot with guidance and control tasks. He found that localized

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Fig. 1. Hardware

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vibration on the pilot's body was easily coupled to spatial information like direction to a waypoint or a threat. A vibrotactile device alerting the pilot about the aircraft attitude is presented by Cardin et al. [13]. Experimental comparison of a haptic aid system and automated pilot were tested and evaluated by [14]. Nieuwenhuizen and B "ulthoff [15] investigated a multimodal interface for personal aerial vehicle control. An active sidestick with spring-like guiding forces together with a highway-in-the-sky-display were designed and tested with the goal to create an easy-to-use control interface for non-expert pilots. Intuitive reactions on directional vibrations applied on a joystick were tested recently [16].

Although the research is focused on pilot-small aircraft interaction, AoA control is an issue for all airplanes. Two accidents of 737MAX [17] [18] happened recently. Both incidents are connected by similar circumstances related to the MCAS system reacting on input from AoA sensor. That is the only assumption of the reason for the accident because the investigation has not been finished yet.

III. Design

The hardware for the experiment comprised a joystick Mad Catz Pacific AV8R with two removable handles (Fig. 1). Haptic feedback actuators were built in these handles. The vibrations were managed by 3V Pancake Cell Phone Coin Vibration Motors. Five vibration motors were mounted on the handle, but only two of them (forward and backward directions) were used in the experiment. The sliding element was powered by two SG90 Digital servomotors. These servomotors were able to move the sliding element continuously. The direction of the movement is perpendicular to the joystick handle surface. It means that it can move out of the surface and also under the surface continuously. Both handle variants were controlled by Arduino Pro Micro microprocessor in Matlab environment.

IV. Evaluation

This chapter describes experiment tasks, haptic feedback functions, and results, which are discussed in the following section.

1) Participants: We recruited 12 participants (2 female, 10 male), average age 28.67 ($SD = 4.28$, $MIN = 22$, $MAX = 36$). All participants could use their dominant hand because of handle symmetry.

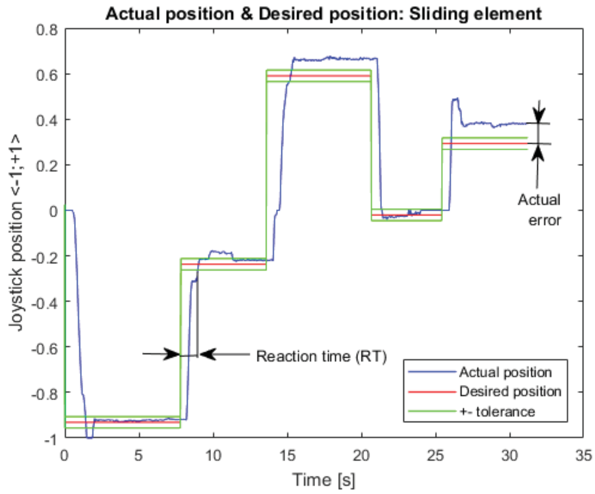

Fig. 2. Task 1 fragment with measured parameters

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2) Procedure: The experiment consisted of two blocks. One block of the test was performed with the vibration motors guidance, and the other was carried out with the sliding element guidance. The first half of the participants started with the vibrations and the second half with the sliding element. Two different tasks were performed within each block.

The first task was to follow the haptic guidance with joystick into 30 randomly generated positions. The vibrations or the sliding element guided the participant to the target position in a haptic way. The target position was supposed to be held until the next target position was generated (Fig. 2). The target positions were generated in the time interval between 5 to 10 seconds. Only the forward and backward direction of the joystick movement was investigated. There was a short four minutes training before the first task with the same task as in the experiment. Two parameters were observed in the first task. The reaction time is the time between the generation of a new target position and its first reaching by the actual position of the joystick. The measurement of the error between the target position and the actual position of the joystick starts after the reaction time passed. The second task followed the first one without any training. It consisted of a 30-seconds record of the joystick forward-backward movement followed by the participants. The participants were again guided by haptic feedback, but this time into following a continuously changing target position. There were two patterns of the target position movement (Fig. 3 and 4). Both patterns were assigned to participants by the Latin square rule to avoid the influence of pattern shape to investigated haptic guiding methods. The mean error between the target position and the actual position of the joystick was evaluated.

3) Guiding methods: The same Guiding method for vibration motors was used as in previous research [19]. A vibration motor in the direction of the target position vibrates with changing pulse duration as the target position gets closer, the pulse duration decreases. There are no vibrations in *tolerance distance* from the target position ($\pm 1.25\%$ of full joystick range). The sliding element continuously moves with a direct proportion to the error between the target and actual position.

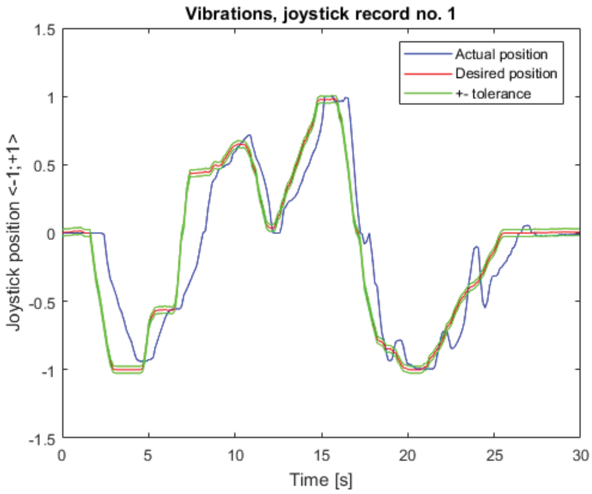

Fig. 3. Task 2, Vibrations, joystick record no. 1

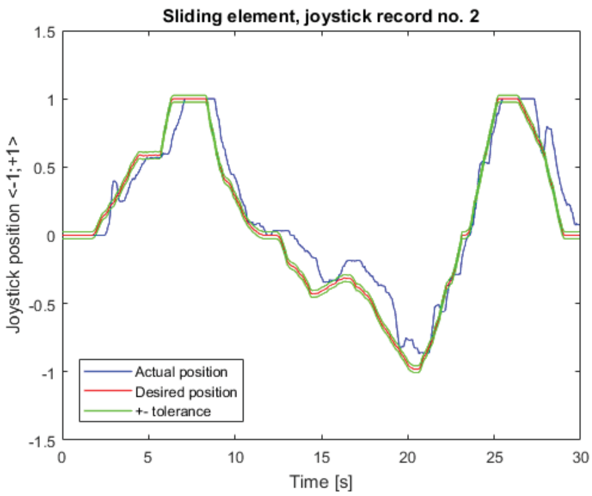

Fig. 4. Task 2, Sliding element, joystick record no. 2

The sliding element moves in the same direction, where is the target position with respect to the actual position.

4) Questionnaire: All subjects were asked to complete a short questionnaire after the experiment. The age and sex of participants were noticed. Then Three questions were given for both methods. The questions Q1 - Q3 aimed at the vibration method and the questions Q4 - Q6 aimed to the sliding element method.

- Q1 (and Q4): Was the method intuitive?
- Q2 (and Q5): Was the method effective?
- Q3 (and Q6): Was the method efficient?

The answers were chosen on a Likert scale with the options (No, Rather no, Neither yes or no, Rather Yes, Yes). The last question was open and asked the participants for subjective comparison of both methods.

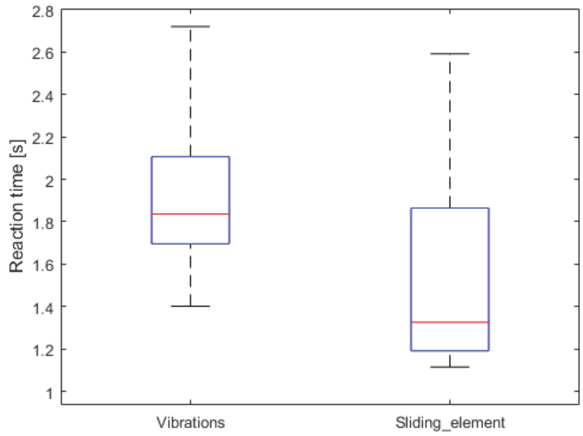

Fig. 5. Reaction time comparison

5) Results: The reaction time and the mean error were evaluated from the results of the first task. Unfortunately, the error between the target and the actual position was evaluated in an incorrect way. Therefore, only the reaction time is presented here (Fig. 5). The reaction time means values for both methods (The vibrations and the sliding element) were compared by Student's t-test. A hypothesis assumed that the mean reaction time was the same. The mean values of the reaction time were 1.904 s with $SD = 0.37s$ for the vibration method and $1.548s$ with $SD = 0.48s$ for the sliding element method. The value of $p = 0.054$ means that the mean reaction time for both methods differed with a confidence level 90% but did not differ with a confidence level 95%.

The central lines on (Fig. 5 and 6) indicates the median of measured values. Top and bottom edges of the box present $25th$ and $75th$ percentiles. The whiskers extend to the approximately 99.3% coverage [20].

The mean error between the target and the actual position was measured in the task 2. (Fig. 3 and 4) show two 30-seconds records of the joystick movement which were supposed to be followed with the guidance of both methods. This task followed the first one without any practice. The influence of different joystick movement records was eliminated by a combination of both records and both methods among the participants. Result of the mean error given in percentage of the joystick range is shown in (Fig. 6). The mean error for the vibration method was 10.61% with $SD = 2.58$. The mean error for the sliding element was 6.671% with $SD = 1.12$. A hypothesis that the mean error was the same for both methods was rejected on a 99% confidence level. The sliding element method gave better results of the mean distance between the target and the actual position than the vibrations method.

Results of the Likert scales are shown in the (Fig. 7) and discussed in the next section. There were some repeated answers to the last open question in the questionnaire. The vibrations were assessed as uncomfortable in prolonged duration of the guidance. This method was better in guiding to the precise target position. The sliding element was assessed as more intuitive and comfortable with better prediction of

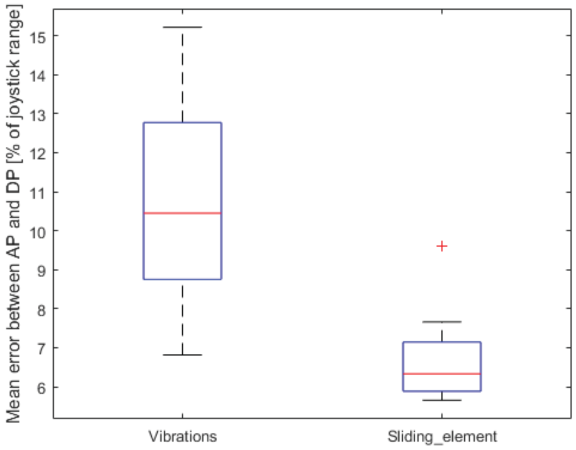

Fig. 6. Mean error comparison

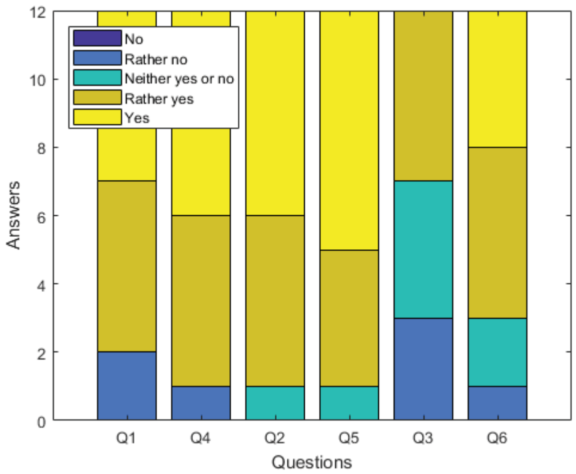

Fig. 7. Subjective assessment of both methods

distance from the actual to the target position. But a final approach to the target position was perceived indeterminate. The sliding element gave better information in the forward direction when moved out of the handle surface-than in backward direction when the element moved inside the joystick, and the participants lost the connection with it.

V. Discussion

The comparison of both methods was carried out by the experiment, both tasks and by subjective evaluations. The results of the reaction time show slightly better values for the sliding element than for the vibrations. These result was confirmed only with a confidence level 90% but did not with a confidence level 95%. The mean error between the target and the actual position were not evaluated quantitatively. The subjective evaluation showed that the vibrations were significantly better than the sliding element for guiding into the target position with the tolerance interval. The reason might be in the haptic feedback functions. The vibrations gave very short and clear signals in case of getting over the tolerance. It gave sufficient instruction to find and especially hold the target position. A haptic feedback function for the sliding element gave only a continuous response proportional to a distance between the target and the actual position. Any clear signalization of the tolerance interval was missing.

The second task results showed a remarkable difference between both methods. The mean error between the target and the actual position was significantly lower for the sliding element method. The reason is the prediction of the joystick required movement with the sliding element method. The vibrations work better for the precise position guiding but provide a worse prediction of the joystick required movement. While the target position was changing the benefit of the sliding element increased against the vibrations.

The participants assessed the sliding element Q4 slightly more intuitive than the vibrations Q1 (Fig. 7). Both methods were rated as effective Q2 (the vibrations) and Q5 (the sliding element). The following questions asked for the efficiency of the methods. The sliding element Q6 was assessed more efficient than the vibrations Q4. Most participants commented that the sliding element was more efficient, especially for task two. That corresponds to the quantitative comparison, where the sliding element gave significantly lower error between the target and the actual position.

Despite the quantitative results, the haptic feedback was perceived individually. The vibrations were described as little painful by two participants after some time of testing. The sliding element was assessed as intuitive, but one participant would prefer the opposite orientation of the element movement. According to Craig and Evans [21], a person continually adapts to constant tactile input. Moreover, the perception of multiple tactile inputs can induce specific sensations. These issues lead to two challenges. The first one is the personalizing of the haptic feedback. Functions for mediating tactile information should have a possibility of personal setup. The second challenge is an investigation of a learning process and an adaption of a participant during long term experiments.

VI. Conclusion and Future Work

The research aims to an improvement of the pilot-aircraft interaction. The haptic feedback is supposed to mediate a feeling of a flow-field around a wing and guide the pilot when a dangerous flight regime is approaching. This research compared two haptic methods for joystick guidance in the forward and backward direction. The vibrations and the sliding element methods have been used for the joystick guidance to the randomly generated target positions as well as to 30-seconds record of fluently changing position. The sliding element method gave a slightly shorter reaction time and smaller error between the target and the actual position than the vibrations. The vibrations method was better only in the precise guidance to keep the target position within the tolerance interval. These results are influenced by the combination of the haptic feedback method and character of the feedback functions. The sliding element with a fluent movement is better for following the continuously changing target position. A discrete pulsation of the vibration motors is better for a small precise movement when the prediction of the movement distance is not demanded.

The future work is expected to deal with personalizing of the haptic feedback. The results cannot be generalized for all pilots because of the different perception of people. Long-term experiments should be carried out to show the learning process of the pilot using the haptic feedback. A pilot's performance improvement during a certain time should be investigated. Experiments on a flight simulator with the haptic feedback joystick could be the best strategy at this stage of the research.

Acknowledgment

This research was supported by TACR, project no. TJ01000122 ”Haptic feedback of assistant systems for flight safety improvement”.

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13th Research and Education in Aircraft Design Conference 2018
Brno, Czech Republic, 7th – 9th November 2018
doi: 10.13164/conf.read.2018.10

VIBRATION FEEDBACKS IN PILOT-AIRCRAFT HAPTIC INTERACTION

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Keywords: haptic feedback, pilot-aircraft interaction, spatial and movement guidance, stall warning, emergency procedures

Abstract: A research about different ways of encoding the distance information with vibrotactile feedback was done as part of a bigger project with the aim of designing a device which would help the pilot to achieve greater precision during the flight. Different kinds of stall warning devices and structural additions were already designed in the field of aviation, lingering only over attentional guidance. Therefore, a lack of spatial and movement guidance was detected. This paper lingers on this research which aimed to encode and evaluate haptic guiding methods.

1 INTRODUCTION

It is well known that the loss of control of an aircraft represents the cause of a large number of accidents in aviation. Various EASA Annual Safety Reviews and other reference safety statistics have repeatedly identified loss of control as a primary accident category in light and heavy aircraft.

Such losses of control usually involve a full stall or an approach to a stall at some stage in the event sequence, whether as the initiating factor or as a later consequence. Even though pilots are taught to recognise, avoid and recover from stalls during the early flight training, yet the inadvertent loss of control continues to occur, with the circumstances of each new accident often similar to those of previous accidents. Different kinds of stall warning devices and structural additions were already designed, with the function of warning the pilot, postponing the stall, preventing it or making it less severe. They linger only over attentional guidance.

Therefore, a lack of spatial and movement guidance was detected. In consequence, the desire to design a device which would help the pilot to achieve greater precision during the flight appeared. A device, which would not just warn the pilot about a dangerous flight mode, but that would guide him into solving it or solving any inefficient way of flying.

As first, two vibration engines representing two directions (forward and backwards) were implemented on a joystick, which represents the control stick of an aircraft. Based on previously done work with similar tasks, a research was done to find different ways of encoding the distance information with vibrotactile feedback. The parameters, which can be manipulated, were defined and studied. Based on this study two parameters – the rhythm and the pulse's duration – were affected in three different combinations – "rhythm only", "only duration", and "rhythm & duration". A pilot test was conducted to define their basic intuitiveness, narrowing the guiding methods into two: "only

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duration" and "rhythm & duration". These two methods were chosen to be tested with a series of tests, in order to evaluate their learnability, accuracy and their intuitiveness. To both methods an additional vibration ("contra vibration") was added. Both versions, with and without "contra vibration" were tested as well.

2 PREVIOUS RESEARCH ON VIBROTACTILE GUIDANCE

The use of vibrotactile feedback as guidance is wide and broadly applied. With the aim of reaching different tasks, numerous applications were developed: as vibrating belts, shoulder pads, dorsal and ventral torso vests, arm and wrists bands. When referring to the tasks of guidance, it is possible to divide them into three categories. Attentional guidance, where vibrotactile feedbacks are used to direct the attention to the location of critical events; movement guidance, where the use of vibrotactile feedbacks is to guide movements and to enhance motor learning and training; and spatial guidance, where vibrotactile stimulation is used directly to guide humans toward a specific target [1].

In the field of aviation various uses of haptic feedback, with the aim of warning the pilot about the onset of a stall and reducing disorientation, were already developed and applied. Devices such as the stick shaker: a stall warning mechanical system, connected to lift detectors and angle of attack sensors, which shakes the control yoke when a stall is imminent [2]. Or such as TSAS – the Tactile Situation Awareness System: the use of a torso harness, fitted with multiple actuators, which can continuously update the pilot's awareness of position [3].

The aim of this project it does not only linger over attentional guidance (i.e. to warn) but it also dwells on spatial and movement guidance (i.e. to guide into a precise way of flying and into solving dangerous flight modes). That is why this work is dedicated to find, to design, to test and to evaluate different guiding methods.

In consequence, a research on the vibrotactile parameters, which can be modified to achieve different guiding methods, follows.

2.1 Affectible parameters

From the parameters, which can affect the vibrotactile feedbacks, different motifs can represent simple actions and, when combined, they can represent even more complex concepts. These kinds of connections between the motifs and their meaning require being learned [4]. To interfere more slightly

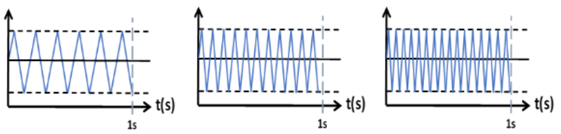

Figure 1: Example of three different frequence's graphs

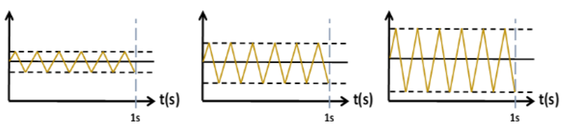

Figure 2: Example of three different amplitude's graphs

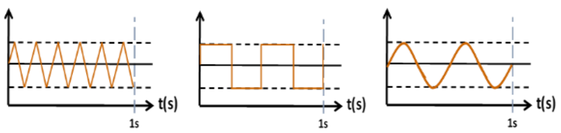

Figure 3: Example of different signal's waveforms

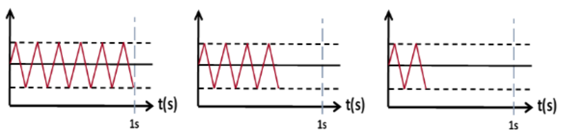

Figure 4: Example of signal's changing duration

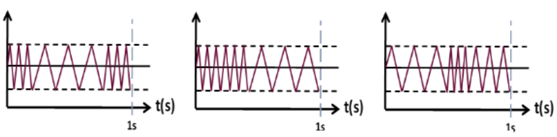

Figure 5: Example of different rhythm paterns

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with the pilot concentration, the reaction of the pilot should be almost automatic. Therefore, one of the aims to achieve is to design guiding methods as simple and as intuitive as possible.

The parameters, which can be manipulated, often vary depending on the type of the actuator. Not all of them allow influencing all the parameters. In general, the tactile affectable parameters are:

- The frequency, which represents the number of cycles per second [5] as shown in Figure 1.
- The amplitude, which defines the strength of the vibration stimuli, which are detected just when the amplitude exceeds a specific threshold [5] – shown in Figure 2.
- The waveform (Figure 3) is a much less important variable because its perception is much more limited. The sine and square waves are possible to differentiate, but slighter differences are almost imperceptible [4].
- When varying the length of a single pulse, we are affecting the duration (Figure 4) of the vibrotactile signal [5].
- The rhythm (Figure 5) represents groups of pulses of different durations which are put in a temporal pattern [5].
- As different locations across the body have different levels of sensitivity and spatial acuity it is possible to use spatially distributed actuators as the variable of body location, which notifies the position of the stimuli [4].

According to [5], the frequency and the amplitude can be treated as one parameter, called intensity, considering that they both change according to the change of voltages, and the change is almost linear.

3 DEVELOPMENT OF THE METHODS

Before starting with the designing of different guiding methods, another experiment was done. During this first experiment, with the aim of examining the human reaction on directional vibration impulses, the hardware was made. A joystick representing the control stick, with four vibration engines representing four main directions (forward, backward, left and right), and one vibration engine simulating interferences caused by aircraft vibrations. As results of this experiment the hypothesis that human can distinguish directional vibrations of a control stick was confirmed. A preferred reaction direction (toward the vibration) was evaluated more intuitive and automatic. The interference caused by the fifth vibration engine did not influence results by either objective or subjective evaluation [6].

When the conclusions mentioned above were made, the developing of different guiding methods started. The first step was to define which variables can be affected. Previous research on vibrotactile guidance showed that five parameters can be modified to encode information in general: intensity, waveform, duration, rhythm, and body location. According to [7], it is not possible to modify the waveform of the signal because its manipulation would require specific hardware. Furthermore, in our case, the body location parameter was already used as the perception of the directions.

In summary, guiding can be conducted by altering just three parameters: intensity, rhythm, and duration. Considering that the intensity is a parameter that can be affected in combination with both, rhythm and duration, and particularly considering that its value should be decided in spite of the interferences caused by the aircraft's vibrations, we decided to set this parameter aside and analyze it in the future. Therefore, the focus lingered just on rhythm and duration.

Consequently, the following options are available: "only rhythm", "rhythm & duration", and "only duration". In order to validate whether all of these options are easy to perceive and to interpret, we investigated them in a first pilot test. To simplify the coding the decision to dwell just with two directions – forward and backward – was taken.

3.1 Pilot test

The pilot test aimed to find out the intuitiveness of the primarily designed guiding methods. The results were supposed to help for a further comparative evaluation. The primary task of each method consisted of following the vibrations to a specific randomly chosen position and trying to hold it. The subject had to perform one trial for each method. Each trial consisted of reaching and holding 21 desired positions (DP). The subject was asked to talk about his perceptions and reactions associated with the vibrotactile feedback.

The movement of the joystick required to achieve the position was toward the direction of the vibrations.

- The “only rhythm” option had five different rhythms varying according to the distance from the DP.
- The “only duration” option consisted of getting shorter vibration pulses the closer the joystick was getting to the DP.
- The “rhythm and duration” option was a combination of both: on further distances, the rhythm patterns were used, but as soon as the joystick reached striking distances to the DP, the “only duration” option took up.

The test aimed to stress out only the intuitiveness of the three different guiding methods mentioned above. Therefore, the average deviation (AE) from the DP, the maximum deviation (ME) from the DP, and the subject's perception were observed.

The subject tested all three options. At the end of the pilot test, the “only rhythm” method was removed. According to the subject’s comments, it was too confusing and not accurate enough considering the relatively high speeds the hand achieved on those really small distances.

3.2 Results and conclusions

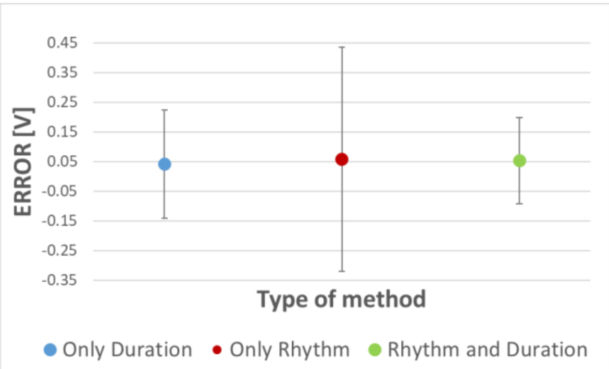

Figure 6: Pilot test - Comparison of the maximum average deviations during each method

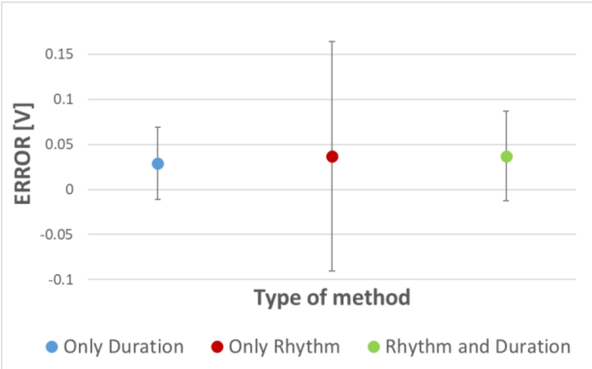

Figure 7: Pilot test - Comparison of the achieved average deviations during each method

Based on the subject assertion, the methods, which were tested, were narrowed into two main guiding methods: the “only duration” and the “rhythm & duration”. This was confirmed by his perception and by a higher ME from the DP and a higher AE measured in the “only rhythm” method as shown in Figure 6 and Figure 7.

With the aim to lower the MEs and the maximum overdrafts of the DP (MODPs), an additional vibration called the “contra vibration” was added to both methods. This vibration occurs only the first time the subject reaches a DP, warning him about it. Both versions, with and without “contra vibration” were tested as well.

4 MAIN TESTING

4.1 Subjects

The methods were tested on 22 subjects, 16 males and 6 females in an age range between 21 and 27. They were randomly divided into two groups – 11 subjects per each method - in order to avoid any alternation during the learning process because of the overlapping of the methods.

4.2 Hardware

The hardware used for the experiment included:

- A joystick, representing the control stick of the aircraft. Genius MaxFighter F-16U was the type of the used joystick, and its potentiometers were connected to the microcontroller for position reading,
- Two mobile phone vibration engines (LG Optimus Black P970) representing direction signaling.
- An Arduino MEGA microcontroller.

The vibration engines were placed on the joystick in two directions – forward and backwards – and fastened by four layers of double-sided tape to insulate joystick from spreading vibrations in all directions as shown in Figure 8. The code was run on Arduino MEGA from MatLab environment.

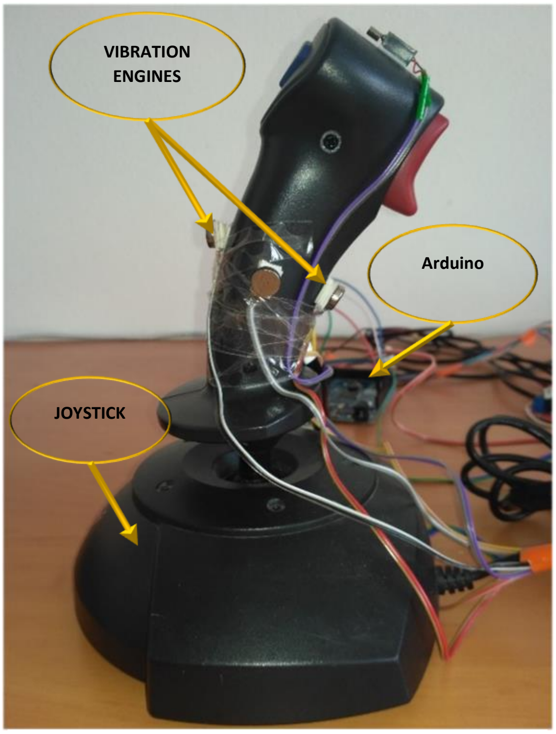

Figure 8: Experimental hardware

	Definition
HT	The *Holding Time* represents the total time in which the subject is able to hold the DP successfully.
LT	The *Learning Time* represents the time that the subject needs to hold the position at least for the first entire second before he makes any deviations from the DP.
DPT	The *Desired Position Time* represents all duration of the DP. Each DP has a different randomly chosen DPT.
AE	The Average Error represents the average value of the deviations made when trying to hold the DP.
ME	The *Maximum Error* represents the maximum value of all the deviations made when trying to hold each DP.
MODP	It represents the maximum value of all the overdrafts made during the holding of each DP. The overdraft is the overcrossing of the DP based on the initial AP.

Table 1: Main measured parameter and their definitions

4.3 Experiment design and procedure

The testing of each subject consisted of three parts.

1. The LEARNING PART in which the subjects were asked to complete the primary task, which consisted of following the vibrations to a specific randomly chosen position and trying to hold it. They had to reach and hold 30 positions to get accustomed to the method. The measurements of this part, compared with the AFTER-LEARNING PART, were used to evaluate the learnability of the method.

2. In the AFTER-LEARNING PART, the subjects were asked to complete the same primary task and to reach and hold 30 positions as well. The measurements of this part were compared with the measurements of the same part of the other method. This comparison was used to evaluate the accuracy of the two methods.
3. The measurements made during the CONTRA-VIBRATION PART while reaching and holding 30 DP with the addition of the “contra-vibration” were compared to the measurements made during the AFTER-LEARNING PART. In this way, they were used to evaluate the usefulness of the “contra vibration”.

All the subjects were asked to tell their perceptions.

Because of the variance of the response, due to the changing of the participants’ attention, the haptic sense was isolated by putting headphones with calm instrumental music on each subject, preventing them from relying on combining the haptic sense with the audible sensing of the vibrations.

The main parameters on which the evaluation was done are explained in Table 1.

4.4 Guiding methods

The explanation of the design of the two guiding methods follows.

The “only duration” method – when a position is chosen, a periodic vibration points the direction in which to move the joystick – i.e. toward the vibrations. The closer the joystick's actual position (AP) gets to the DP, the shorter the pulse's duration gets.

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The “rhythm and duration” method – when a position is chosen, a periodic vibration points the direction in which to move the joystick – i.e. toward the vibrations. The rhythm of the vibrations changes in accordance with the distance between the AP and the DP. There are 3 different rhythms connected to this distance (»Far distance«, » Closer distance«, » Striking distance« - shown in Figure 9). When the joystick is in the »Striking distance«, the vibration gets in the same modality as in the »only duration« method: the closer the joystick's AP gets to the DP, the shorter the pulse's duration gets.

For both methods - when the DP is reached, there are no more vibrations. The same is applied when the position is held successfully. If the joystick is moved from the DP, a periodic vibration points the direction in which to make the correction. The pulse's length depends on the distance between the DP and the AP. The subject’s main task is to reach and hold the position as precisely as possible until the next one is not chosen and pointed by the vibrations.

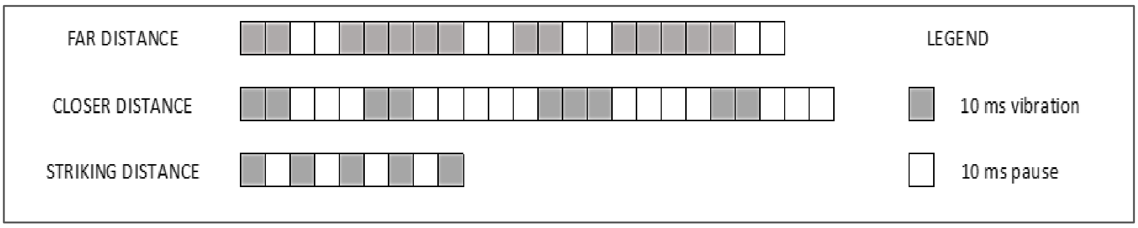

Figure 9: Rhythm patterns of the »rhythm&duration« method.

5 EVALUATION AND RESULTS

Based on the measured parameters a series of hypothesis tests were conducted to evaluate the accuracy of each method, the usefulness of the “contra vibration” and the learnability of each method.

5.1 The accuracy of the methods

H0: $\mu_{AEs\_OnlyDuration} - \mu_{AEs\_Rhythm\&Duration} = 0$		
Ha: $\mu_{AEs\_OnlyDuration} - \mu_{AEs\_Rhythm\&Duration} > 0$		
	AEs_OD	**AEs_R&D**
Mean [V]	0.065	0.079
Variance [V]	0.0022	0.0034
Observations [/]	330	330
Hypothesized Mean Difference	0	
df	631	
t Stat	3.497	
P(T<=t) one-tail	0.00025	
t Critical one-tail	1.647	

Table 2: Results of the t-test made with the comparison of the AEs achieved by the subjects during the AFTER-LEARNING PART

H0: $\mu_{MEs\_OnlyDuration} - \mu_{MEs\_Rhythm\&Duration} = 0$		
Ha: $\mu_{MEs\_OnlyDuration} - \mu_{MEs\_Rhythm\&Duration} > 0$		
	MEs_R&D	**MEs_OD**
Mean [V]	0.228	0.181
Variance [V]	0.0679	0.0449
Observations [/]	330	330
Hypothesized Mean Difference	0	
df	632	
t Stat	2.578	
P(T<=t) one-tail	0.0051	
t Critical one-tail	1.647	

Table 3: Results of the t-test made with the comparison of the MEs achieved by the subjects during the AFTER-LEARNING PART

H0: $\mu_{HTs\_OnlyDuration} - \mu_{HTs\_Rhythm\&Duration} = 0$		
Ha: $\mu_{HTs\_OnlyDuration} - \mu_{HTs\_Rhythm\&Duration} > 0$		
	HTs_OD	**HTs_R&D**
Mean [s]	10.49	8.53
Variance [s]	32.85	28.63
Observations [/]	330	330
Hypothesized Mean Difference	0	
df	655	
t Stat	4.55	
P(T<=t) one-tail	0.000003	
t Critical one-tail	1.647	

Table 4: Results of the t-test made with the comparison of the HTs achieved by the subjects during the AFTER-LEARNING PART

In order to evaluate the accuracy of the methods, three two-sample one-tailed t-tests with a level of confidence of 95% were performed. Each of them is comparing the two methods through one of the parameters (AEs, MEs and HTs) achieved by the subjects during the AFTER-LEARNING PART.

For each test the three conditions for valid t-intervals were reached:

- The data was a random sample from the population of interest,
- The sampling distribution of the sample was approximately normal (n° of measurements ≥ 30),
- The individual observations can be considered independent.

1. The AEs achieved by the “only duration” method subjects were significantly lower (P = 0.00025) than those achieved by the “rhythm & duration” method subjects. The results of the test are shown in Table 2. Figure 10 is an example of the frequency of the measured AEs as an approximately normal distribution.
2. The MEs achieved by the “only duration” method subjects were significantly lower (P = 0.0051) than those achieved by the “rhythm & duration” method subjects. The results of the test are shown in Table 3.
3. The HTs achieved by the “only duration” method subjects were significantly higher (P = 0.000003) than those achieved by the “rhythm & duration” method subjects. The results of the test are shown in Table 4.

In conclusion, all three tests asserted that the "only duration" method is significantly more accurate than the "rhythm & duration" method, with lower achieved AEs and MEs, and with higher achieved HTs.

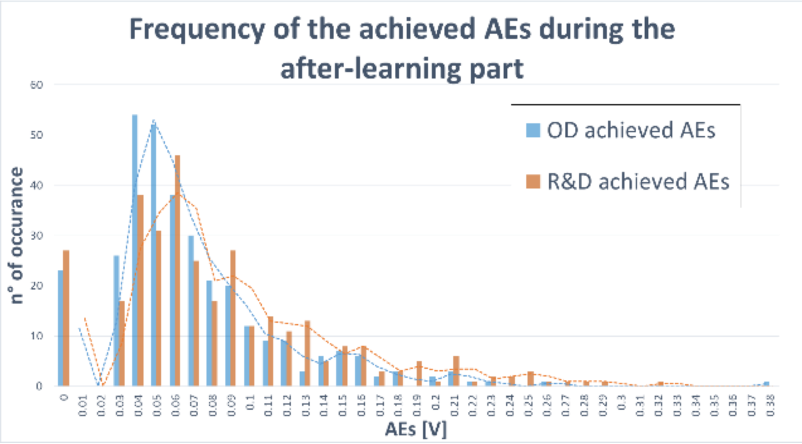

Figure 10: The Frequency of the measured AEs during the AFTER-LEARNING PART

5.2 The usefulness of the "contra vibration"

To evaluate the effects of "the contra vibration" three one-tailed paired t-test conducted with a confidence level of 95% were performed for each method. Each of them compared parameters (AEs, MEs and MODPs) achieved by the subjects during the AFTER-LEARNING PART and the CONTRA-VIBRATION PART. For each test, the three conditions for valid t-intervals were reached.

Assertions for the "only duration" method

1. The difference between the achieved AEs during the CONTRA-VIBRATION PART and the AFTER-LEARNING PART of the testing was not significant enough (P = 0,264) to assert that there is an improvement thanks to the addition of the »contra vibration«. The results of the test are shown in Table 5.
2. The difference between the achieved MEs during the CONTRA-VIBRATION PART and the AFTER-LEARNING PART of the testing was not significant enough (P = 0,315) to assert that there is an improvement thanks to the addition of the contra vibration. The results of the test are shown in Table 6.
3. The difference between the achieved MODPs during the CONTRA-VIBRATION PART and AFTER-LEARNING PART of the testing was not significant enough (P = 0,283) to assert that there is an improvement thanks to the addition of the contra vibration. The results of the test are shown in Table 7.

Assertions for the "rhythm & duration" method

1. The AEs achieved during the CONTRA-VIBRATION PART are significantly higher (P = 0, 0000012) than those achieved during the AFTER-LEARNING PART. The results of the test are shown in Table 8.
2. The MEs achieved during the CONTRA-VIBRATION PART are significantly higher (P = 0, 000013) than those achieved during the AFTER-LEARNING PART. The results of the test are shown in Table 9.
3. The MODPs achieved during the CONTRA-VIBRATION PART are significantly higher (P = 0, 0097) than those achieved during the AFTER-LEARNING PART. The results of the test are shown in Table 10.

In conclusion, the tests performed on the “only duration” method asserted that the addition of the “contra vibration” had not led to any significant improvement to any of the measured parameters.

Those performed on the “rhythm & duration” method asserted that the addition of the “contra vibration” led to a significant decrease of the accuracy affecting all three parameters negatively.

Beside it, 18 subjects out of 22 affirmed that the “contra vibration” strongly confused them because of a sudden additional vibration that made them react with additional movements and less accuracy. Based on their assertions the “contra vibration” is confusing and not that much intuitive.

H0: $\mu_{AEs\_NONCONTRA} - \mu_{AEs\_CONTRA} = 0$		
Ha: $\mu_{AEs\_NONCONTRA} - \mu_{AEs\_CONTRA} > 0$		
	AEs_NONC	AEs_C
Mean [V]	0.065	0.067
Variance [V]	0.0022	0.0033
Observations [/]	330	330
Hypothesized Mean Difference	0	
df	329	
t Stat	-0.6302	
P(T<=t) one-tail	0.264	
t Critical one-tail	1.967	

Table 5: »Only duration« method - Results of the t-test made with the comparison of the AEs achieved by the subjects during the AFTER-LEARNING PART and the CONTRA-VIBRATION PART

H0: $\mu_{MEs\_NONCONTRA} - \mu_{MEs\_CONTRA} = 0$		
Ha: $\mu_{MEs\_NONCONTRA} - \mu_{MEs\_CONTRA} > 0$		
	MEs_NONC	MEs_C
Mean [V]	0.177	0.185
Variance [V]	0.041	0.062
Observations [/]	330	330
Hypothesized Mean Difference	0	
df	329	
t Stat	-0.482	
P(T<=t) one-tail	0.315	
t Critical one-tail	1.649	

Table 6: »Only duration« method - Results of the t-test made with the comparison of the MEs achieved by the subjects during the AFTER-LEARNING PART and the CONTRA-VIBRATION PART

H0: $\mu_{MODPs\_NONCONTRA} - \mu_{MODPs\_CONTRA} = 0$		
Ha: $\mu_{MODPs\_NONCONTRA} - \mu_{MODPs\_CONTRA} > 0$		
	MODPs_NONC	MODPs_C
Mean [V]	0.156	0.147
Variance [V]	0.04	0.042
Observations [/]	330	330
Hypothesized Mean Difference	0	
df	329	
t Stat	0.574	
P(T<=t) one-tail	0.283	
t Critical one-tail	1.649	

Table 7: »Only duration« method - Results of the t-test made with the comparison of the MODPs achieved by the subjects during the AFTER-LEARNING PART and the CONTRA-VIBRATION PART

H0: $\mu_{AEs\_NONCONTRA} - \mu_{AEs\_CONTRA} = 0$		
Ha: $\mu_{AEs\_NONCONTRA} - \mu_{AEs\_CONTRA} > 0$		
	AEs_NONC	AEs_C
Mean [V]	0.079243711	0.106181
Variance [V]	0.003396168	0.007194
Observations [/]	330	330
Hypothesized Mean Difference	0	
df	329	
t Stat	-4.801	
P(T<=t) one-tail	0.0000012	
t Critical one-tail	1.649	

Table 8: »Rhythm&duration« method - Results of the t-test made with the comparison of the AEs achieved by the subjects during the AFTER-LEARNING PART and the CONTRA-VIBRATION PART

H0: $\mu_{MEs\_NONCONTRA} - \mu_{MEs\_CONTRA} = 0$		
Ha: $\mu_{MEs\_NONCONTRA} - \mu_{MEs\_CONTRA} > 0$		
	MEs_NONC	MEs_C
Mean [V]	0.228425749	0.336433
Variance [V]	0.067927032	0.166388
Observations [/]	330	330
Hypothesized Mean Difference	0	
df	329	
t Stat	-4.262	
P(T<=t) one-tail	0.000013	
t Critical one-tail	1.649	

Table 9: »Rhythm&duration« method - Results of the t-test made with the comparison of the MEs achieved by the subjects during the AFTER-LEARNING PART and the CONTRA-VIBRATION PART

H0: $\mu_{MODPs\_NONCONTRA} - \mu_{MODPs\_CONTRA} = 0$		
Ha: $\mu_{MODPs\_NONCONTRA} - \mu_{MODPs\_CONTRA} > 0$		
	MODPs_NONC	MODPs_C
Mean [V]	0.199561585	0.255134
Variance [V]	0.067717423	0.126208
Observations [/]	330	330
Hypothesized Mean Difference	0	
df	329	
t Stat	-2.345	
P(T<=t) one-tail	0.0097	
t Critical one-tail	1.649	

Table 10: »Rhythm&duration« method - Results of the t-test made with the comparison of the MODPs achieved by the subjects during the AFTER-LEARNING PART and the CONTRA-VIBRATION PART

 doi: 10.13164/conf.read.2018.10

5.3 The learnability of the methods

To evaluate the learnability of each method the ratios between the HTs and the DPTs achieved during the LEARNING PART were compared with those achieved during the AFTER-LEARNING PART. This was done separately for each subject with a one-tailed paired t-test with a level of confidence of 95%.

The same comparison was performed with the LTs parameter.

For each test, the three conditions for valid t intervals were reached.

Only four subjects out of eleven tested on the “only duration” method reached a significant improvement in the HT ratios (P-values – 0.00019, 0.015, 0.0034, 0.042) and a significant improvement in the LTs (P-values – 0.013, 0.031, 0.031, 0.0004).

Whereas nine subjects out of eleven tested on the “rhythm & duration” method reached a significant improvement in the HT ratios (P-values – 0.0083, 0.046, 0.0073, 0.0018, 0.0019, 0.048, 0.000004, 0.00028, 0.0159), and seven out of eleven reached a significant improvement in the LTs (P-values – 0.003, 0.016, 0.029, 0.007, 0.0001, 0.0003, 0.026).

In conclusion, it is possible to assert that the »only duration« method achieved fewer improvements during the learning process than the »rhythm & duration« method. This can be explaned taking in consideration the previously done conclusions: the »only duration« method achieved a greater accuracy from the subjects, that's why the improvements done from the LEARNING PART to the AFTER-LEARNING PART are significantly smaller, unperceivable or inexistent.

6 CONCLUSIONS

After defining the parameters which can be manipulated, three different affectable combinations where designed: “duration only”, “rhythm only” and “rhythm & duration”. The pilot test narrowed them into two – “duration only” and “rhythm & duration”. To both methods the “contra vibration” was added, with the aim of increasing the accuracy. The two methods and the “contra vibration” were tested with a series of hypothesis tests. Based on the results:

- The “only duration” method was defined significantly more accurate than the “rhythm & duration” method;
- The “contra vibration” led to no significant improvements for the “only duration” method and a significant decrease in the accuracy of the “rhythm & duration” method;
- The “rhythm & duration” method achieved greater improvement during the learning process than the “only duration” method.

ACKNOWLEDGEMENTS

This research was partially supported by TACR, project no. TJ01000122 "Haptic feedback of assistant systems for flight safety improvement" and by the Erasmus+ programme of the European Union.

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MATEC Web of Conferences **304**, 06005 (2019) https://doi.org/10.1051/matecconf/201930406005
EASN 2019

Flight Test of Pilot-Aircraft Haptic Feedback System

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Abstract. This research is focused on an innovative improvement of pilot-aircraft interaction and is targeted on small aircraft. Haptic feedback is performed by actuators mounted on an aircraft's controls. The purpose of the actuators on a control stick and pedals is stall warning and a pilot guiding to safe and economical flight regimes. The feedback system mediates airflow data as angles of attack and sideslip. The paper brings results of a flight test of the proposed system. Qualitative evaluation of the haptic feedback inflight is presented. Benefits of the system are presented on a sideslip during turning. Some recommendations for the haptic pilot-aircraft interaction are stated within the discussion of the flight test results.

1 Introduction

The control of small aircraft works on the same principle as the control of big airliners, but one aspect is changing recently. Airliners are heading to autonomous flights. Pilots are not required in airlines because of the airplane's physical control but mostly because of the passenger's thrust and safety [1]. The same trend shows the research of Single-Pilot-Operations [2], which leads to a replacement of a second pilot by advanced onboard automation and/or ground operators providing pilot support services. The situation in small aircraft control is different. Sport and leisure time pilots want to keep control of airplanes. At the same time, a human factor is the most common accident reason which leads to a fatal stall/spin or loss of control accidents. This statistic is stated by EASA and NTBS [3, 4]. Ballistic parachute systems are the best current solution to the loss of control. Company Galaxy recently stated that 95 lives were saved by their system [5]. This research aims to prevent those situations in which rescue systems are required. The improvement of the pilot-airplane interaction is supposed to make the airplane control more intuitive. A decrease in a pilot workload and improvement of a pilot's situational awareness are expected at the same time [6].

Haptic feedback promises such improvement in aircraft control. The survey [6] shows that the transfer of some sensations from visual modality to a touch modality could better utilize the pilot's attention. Beeftink et al. stated [7] that haptic feedback in aircraft control could decrease pilot head-down time on behalf of head-up time on a flight simulator. Active controls providing haptic feedback were designed and tested on a flight simulator [8] in a recent project. Shape morphing and vibrations were compared for control stick guidance [9]. This endeavour leads to a hardware setup with a combination of both functions. The moving element is implemented into the control stick and vibration motors are mounted to the rudder pedals. The vibration pedals application is similar to US patent [10] where

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pedals indicate sideslip measured by pressure sensors. The active control stick and pedals hardware were tested on a flight simulator at first. After that, a need to verify the function of the hardware in a real aircraft operation appeared. The process of flight test and the results are described in this paper.

The haptic feedback system function and hardware, as well as flight test setup, are described in the following section. The hardware was mounted and tested on ultralight aircraft Dynamic WT-9. A methodology and results of the flight test are stated in the next sections. The discussion section consists of qualitative and quantitative assessment and recommendations for haptic feedback aircraft control applications.

2 Haptic feedback system

Haptic feedback system itself consists of sensors, a control unit and haptic elements located in pedals and a control stick handle. Input data are obtained from vanes for the angle of attack (AoA) and angle of sideslip (AoS) measurement and processed by the control unit, which operates the active elements accordingly. AoA is linearly transformed into symmetrical extension and retraction of an active element on the control stick handle. AoS is linearly transformed into asymmetrical extension and retraction of the same active element resulting in tilting movement on the respective side of the airplane sideslip. Both movements can be sensed by the pilot's fingers. When AoS exceeds predefined level, pedal vibration on the respective side is activated. AoS is then negotiated by pressing the vibrating pedal. Pedal vibrations use the pulsing pattern instead of continuous vibrations.

2.1 Hardware

The aircraft used for the flight test is a low-wing, single-engine, 2-seats ultralight airplane Dynamic WT-9. A pitot tube with AoA and AoS vanes was used and fixed under the wing of the airplane. The accelerometer [11] was used and fixed inside the cockpit for the flight data evaluation purposes. The control unit was based on an Arduino mega board [12] with data logger shield for flight data recording. The control unit allowed the inflight monitoring of the haptic system using LCD and changing of the haptic feedback system parameters and operation modes. All electronics parts of the control unit were enclosed in 3D printed (PLA) box. 3D printed (PLA) control stick handle includes two servomotors used for the movement of the active element. The handle was strapped to the airplane's control stick so it would not restrict any of the required movements. Each 3D printed (PLA) rudder pedal extension holds two vibration engines [13].

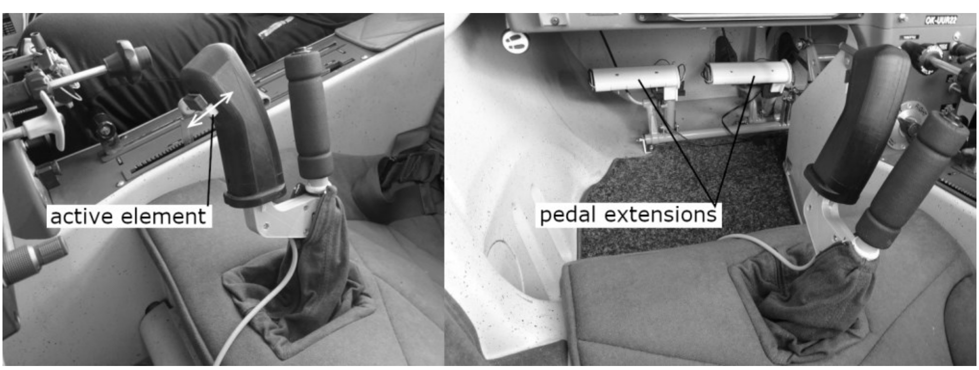

Fig. 1. Haptic feedback actuators on the control stick and the pedals.

Pedal extensions were fixed to the rudder pedals with several separating layers of microporous rubber to prevent vibration propagation into the aircraft control system.

3 Methods

The flight test of the haptic feedback system consisted of the following tasks. The test started by calibration and continued by a subjective assessment, and 360 degrees turns. The goal of the calibration part was to set up reference values of input and output parameters. Zero AoS in symmetric flight was corrected by offset value in horizontal flight. AoA in reference regimes was read and the active element positions were adjusted in required positions. Reference positions of the active element were given by a reference element placed above the active element and by the surface of the control stick handle. The outer reference position marked by the reference element corresponds to AoA at minimal practicable speed. The inner reference position marked by the handle surface corresponds to AoA at the cruise regime speed.

The subjective assessment aimed to inflight verification of the haptic feedback by a pilot. This task was repeated on different speeds within the range between safe near-stall and maximal speed. The pilot commented intensity of rudder pedals vibrations after sideslip flight was induced. There were two issues to be check. The first was possible spreading of vibrations from one pedal to the opposite pedal. The second issue was interference between natural aircraft vibrations induced by the propulsion system and flow field. Positions and function of the active element on the control stick were tested at the same speeds as vibrations of rudder pedals.

The last test task was 360 degrees turns. Left and right turns were performed. One half was flown without the haptic feedback and the second was with the haptic feedback. The haptic feedback was alternately switched on and off to avoid learning effect. AoS was measured as a parameter for the haptic feedback system evaluation. The first hypothesis was: Haptic feedback decreases the mean value of sideslip angle during turning. The second hypothesis was: Haptic feedback decreases sideslip angle above the vibration threshold, which was set up to 5 degrees.

4 Evaluation

The haptic feedback system was assessed in horizontal straight flight at first. The range of AoA to be used with the active element position inflight was measured as a part of calibration of the system. The maximal AoA was measured in horizontal flight at minimal practicable airspeed. The AoA for flaps 0, 15, 24 degrees was 19, 18, 18 degrees respectively at airspeeds of 100, 85, 80 km/h respectively. The minimal AoA was 7 degrees measured at cruising speed of 180 km/h with flaps retracted. These angles were measured from the estimated horizontal aircraft axis; therefore, the absolute values are rather high. The active element was described by the pilot as well sensible with changes in AoA but with continuous wobbling movement that was rather disturbing.

Onboard gauges were used to achieve flight with zero AoS at cruising speed of 180 km/h. It was checked that vanes for the haptic feedback system were also reading 0 at that regime. Afterward, the flight with sideslip was induced by the pilot. Vibration haptic feedback activated when onboard sideslip indicator shows half of the ball out of the bracket at the cruise speed. The pilot commented vibrations as well as sensible and sidewise unambiguous, even better than on the flight simulator with similar haptic feedback system he tried before. The same sequence was used to check the behaviour of sideslip signalization of the control stick element with tilting movement. Recognizability was assessed as considerably worse than the one of vibrating pedals. Moreover, the pilot said that this feedback could guide him into the roll input with the opposite effect of increasing the sideslip.

Twelve horizontal turns were performed on the indicated airspeed 140 km/h. The average sideslip was evaluated in the following way. The angle of sideslip range was cut into small intervals. Counting of sideslip angles for each interval gave its distribution. The distribution was normalised by dividing of measured record length. This normalised distribution of sideslip angle was evaluated for each turn separately and for combined groups of turns with and without haptics (Fig. 2). Normalised angle of sideslip was counted by the integration of the distribution by AoS. The resultant normalised sideslip angles were compared by one-tailed t-test. Mean values of normalised sideslip angles in the turns without haptics is (M = 1.86 deg, SD = 0.78 deg) and in turns with haptics is (M = 1.66 deg, SD = 0.43 deg). It means, that the difference is not statistically significant, $t(10) = 0.54$, $p = 0.30$. The count of flight time when aircraft sideslip was greater than given threshold 5 deg was also evaluated from normalised distributions of the sideslip. The time when the sideslip was greater than the threshold was (M = 4.32, SD = 6.06) percent of the total time without haptics and (M = 2.60, SD = 2.84) percent of total time with haptics. That means, that haptics decreased sideslip angles above the threshold, but the difference is not statistically significant, $t(10) = 0.63$, $p = 0.27$.

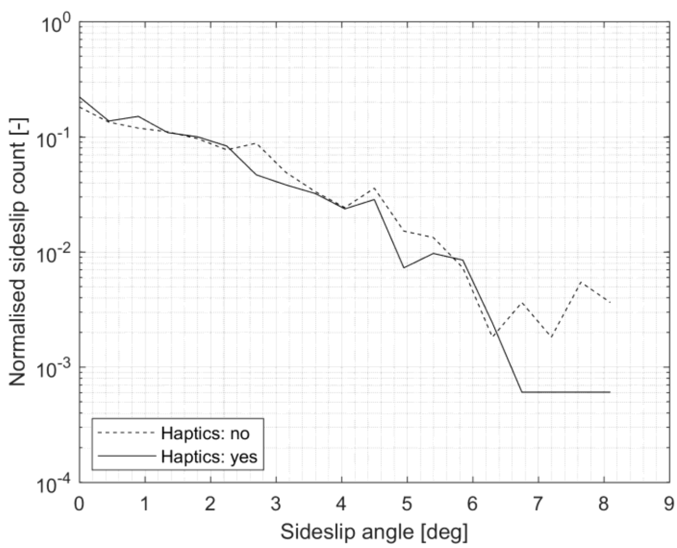

Fig. 2. Normalised sideslip angle distribution with and without haptics.

5 Discussion

The active element of the control stick was described by the pilot as well sensible but with disturbing continuous wobbling movement. That movement of the control stick active element was partially caused using insufficient filtering of AoA input in the control unit and by coarse digital conversion, which caused insensitive AoA input. That also limited the data for the qualitative assessment of the turns. Changes to filtering and digital conversion are expected to resolve the deficiency in the future.

In the beginning, during past flight simulator tests, some pilots doubted whether vibrations as haptic feedback are suitable for motorized aircraft. We were concerned that vibrations would interfere with the airplane engine vibrations and that vibration of one pedal would spread to the other pedal devaluating the haptic feedback completely. However, vibrations of the haptic pedals were commented by the pilot as well sensible and sidewise unambiguous after the flight test in the whole range of tested speeds. That is an improvement compared to the flight simulator test conducted previously with a similar haptic feedback system. The flight simulator rudder pedals have parallelogram guidance of the pedals with a short mechanical link between the pedals. The airplane used for the flight tests has T-shaped rudder pedals with a longer and less stiff mechanical link between the pedals. That combined with a change in treadles shape and therefore change in pedals attachments housing the vibration motor, lead to the improvement of directional sensibility of rudder pedal vibrations. One of the control stick functions had the same purpose as the vibrating pedals. Tilting movement of the control stick active element was assessed as ambiguous and non-intuitive for sideslip information mediation. The pilot was confused by perceiving both AoA and AoS through the moving element at the same time. Tilting movement of the control stick active element was concluded to be more suitable for a roll instead of yaw guidance. A pilot limb would be perceiving and acting in that case. Roll guidance by the tilting function of the control stick seems to be promising and should be analysed.

Quantitative evaluation of the haptic feedback benefit was tested on the aircraft sideslip during 360 degrees turns. The overall sideslip decreased in case of flight with the haptic feedback, but the improvement was not statistically significant. That could be caused by a small statistical sample. Also, sample turns were all flown by a single pilot. It is expected that the perception and influence of haptic feedback may be strongly personal-related. The test pilot did not complete training of using the haptic feedback system. He only had experience from two-hours flight simulator test, which he participated 5 months before flight test. Figure 2 presents normalised sideslip distribution during twelve 360 degrees turns. There is a visible decrease of sideslip with haptic feedback around sideslip 5 degrees and over 6.3 degrees. It corresponds to the threshold of 5 degrees when the pedals vibrations were activated. It can be supposed that the decrease in the threshold value would help to decrease a sideslip during flight. The threshold level should be decreased only to an appropriate level. A too low value would lead to excessively frequent haptic information that would disturb a pilot during the flight with no further positive effect. The second assumption for the haptic feedback benefit improvement is a pilot training on usage of the haptic feedback system. The system is designed to be intuitive, but ongoing research shows a significant learning effect for this pilot-aircraft interaction.

The last point to be discussed is the system suitability for small aircraft. For the testing purposes, vanes located on the pitot tube were used to measure the AoA and AoS. But this solution is impractical for small aircraft mostly because of its price and vulnerability during ground handling. Supposed solution for a commercially offered system of this kind is expected to include AoA pitot tube that uses only pressure measurements for AoA sensing and lateral accelerometer to substitute the AoS measurements by the acceleration measurements. The same approach with lateral acceleration for sideslip indication is used in widely spread avionics systems like [14, 15].

6 Conclusions

The flight test of the haptic feedback system with active element on the control stick and vibration rudder pedals was conducted on the small aircraft. The goal of the flight test was to verify the usability of the haptic feedback previously tested only in a flight simulator. Readability of the active element in the control stick and vibration rudder pedals was assessed positively. Qualitative assessment of the haptic system showed a positive influence on pilot performance in turning flight, but the benefit was not statistically significant. The flight tests revealed some deficiencies that need to be resolved in future development. Complex testing, including pilot training, was recognised as the following step to gain the best profit of the haptic feedback system. In general, the results showed promising potential of the haptic feedback system as an improvement of a pilot-aircraft interaction.

This research was supported by TACR, project no. TJ01000122 "Haptic feedback of assistant systems for flight safety improvement".

Abbreviations

AoA	angle of attack
AoS	angle of sideslip
M	mean value
PLA	polylactic acid
SD	standard deviation

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UŽITNÝ VZOR

(11) Číslo dokumentu:

32 930

(13) Druh dokumentu: **U1**

(51) Int. Cl.:

B64C 13/10 (2006.01)
B64C 13/04 (2006.01)

(19) ČESKÁ REPUBLIKA

ÚŘAD PRŮMYSLOVÉHO VLASTNICTVÍ

(21) Číslo přihlášky: **2019-36079**
(22) Přihlášeno: **02.04.2019**
(47) Zapsáno: **10.06.2019**

(73) Majitel:
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Systém spojený s hlavicí řídicí páky letadla pro hmatové zprostředkování informací pro zachování bezpečného režimu letu

CZ 32930 U1

Systém spojený s hlavicí řídicí páky letadla pro hmatové zprostředkování informací pro zachování bezpečného režimu letu

Oblast techniky

Hmatové zprostředkování informací pro zachování bezpečného režimu letu řeší problém, kdy může dojít ke ztrátě ovladatelnosti letadla v důsledku překročení maximálního úhlu náběhu (letadlo přejde do režimu pádu). Ještě nebezpečnější situace nastává při současném vybočení (letadlo může přejít do vývrtky nebo do pádu po křídle). Pokud k takové situaci dojde v blízkosti země (zejména po vzletu nebo při přiblížení) mohou být následky fatální.

Dosavadní stav techniky

Letadla jsou vybavena rychloměry, které vizuální cestou informují pilota o rychlosti letu a v dnešní době i často systémy varování před pádem, které buď vizuálně nebo zvukově varují pilota při přiblížení se kritickému úhlu náběhu. Dopravní a vojenské letouny bývají vybavené i indikací úhlu náběhu (anglicky Angle of Attack, ve zkratce AoA), která je z pohledu pilotáže a případné ztráty rychlosti a řiditelnosti důležitější než klasický rychloměr.

Nevýhodou vizuální indikace rychlosti (rychloměr), vybočení (příčný relativní sklonoměr) a úhlu náběhu (indikátor úhlu náběhu) je, že zpravidla vyžadují vědomé odečítání prostřednictvím tzv. centrálního vidění. V takovém případě pilot musí věnovat značnou část pozornosti odečítání hodnot na těchto přístrojích. V případě letů za snížené viditelnosti (VFR) a v blízkosti země musí pilot současně věnovat maximum pozornosti situaci v okolí (zachování situačního povědomí, dodržení odstupu od překážek a ostatních letadel).

Nevýhodou zvukových varování o blížícím se překročení maximálního úhlu náběhu je relativně krátká časová prodleva, pokud tato situace nastává příliš rychle. Zároveň zvukové varování nezprostředkovává informaci o případném úhlu vybočení (anglicky Angle of Slip, ve zkratce AoS). Další nevýhodou je možná interference z dalšími zdroji zvuku (komunikace prostřednictvím rádia, hovor v kabině, hluk motoru).

Větší letouny bývají standardně vybaveny systémy shaker a pusher. Shaker vibracemi varuje před přiblížením k pádu, pokud pilot nezareaguje, pusher potlačí sám řízení, čímž dojde k úpravě trajektorie letu směrem ke klesání a zvýšení rychlosti letu. Nevýhodou systémů typu shaker je relativně krátká časová prodleva, zejména při rychlé změně úhlu náběhu. Tyto systému také neposkytují informaci o úhlu vybočení. Nevýhodou systémů pusher je jejich komplexnost a s tím spojená možnost vyšší poruchovosti a také vysoká cena.

Podstata technického řešení

Výše uvedené nedostatky odstraňuje systém spojený s hlavicí řídicí páky letadla podle předkládaného technického řešení, který umožňuje kontinuální předávání informace o úhlu náběhu (AoA) a úhlu vybočení (AoS) prostřednictvím hmatu. Je možné vnímat nejen absolutní hodnotu zmíněných parametrů, ale i rychlost jejich časové změny.

Podstatou tohoto systému je, že obsahuje člen pro hmatové zprostředkování informací, který je osazen do hlavice řídicí páky tak, že v alespoň jedné své poloze má tento člen pro hmatové zprostředkování informací část přečnívající povrch hlavice řídicí páky v oblasti určené pro úchop. Tato přečnívající část obsahuje alespoň jeden element, který je pohyblivý vůči povrchu hlavice řídicí páky, přičemž člen pro hmatové zprostředkování informací je pomocí alespoň jednoho dílu přenášejícího mechanický pohyb propojen s alespoň jedním servomotorem. Tento servomotor je přitom datově propojen s řídicí jednotkou, která je přímo nebo přes další součásti datově propojena s alespoň jedním zdrojem informací o letových parametrech.

Zdroje informací o letových parametrech jsou s výhodou vybrány ze skupiny obsahující senzor úhlu náběhu, senzor úhlu vybočení, počítač letových dat.

Je-li zdroj informací o letových parametrech vybrán ze skupiny obsahující senzor úhlu náběhu a počítač letových dat, je výhodné, když je člen pro hmatové zprostředkování informací v oblasti určené pro úchop hlavice řídicí páky alespoň částečně vysunutelný směrem vně od povrchu hlavice řídicí páky. Míra vysunutí je přitom měnitelná podle údajů ze senzoru úhlu náběhu nebo z počítače letových dat.

Je-li zdroj informací o letových parametrech je vybrán ze skupiny obsahující senzor úhlu vybočení a počítač letových dat, je výhodné, když je člen pro hmatové zprostředkování informací v oblasti určené pro úchop hlavice řídicí páky alespoň částečně tvarově modifikovatelný s měnitelnou mírou asymetrie podle údajů ze senzoru úhlu vybočení nebo z počítače letových dat. Toto provedení lze s výhodou kombinovat s předchozím, v němž je člen pro hmatové zprostředkování informací také vysunutelný a míra vysunutí je měnitelná podle údajů ze senzoru úhlu náběhu nebo z počítače letových dat.

Je-li zdroj informací o letových parametrech je vybrán ze skupiny obsahující senzor úhlu vybočení a počítač letových dat, je výhodné, když je člen pro hmatové zprostředkování informací v oblasti určené pro úchop hlavice řídicí páky alespoň částečně tvarově modifikovatelný s měnitelnou mírou asymetrie podle údajů ze senzoru úhlu vybočení nebo z počítače letových dat. Toto provedení lze s výhodou kombinovat s předchozím, v němž je člen pro hmatové zprostředkování informací také vysunutelný a míra vysunutí je měnitelná podle údajů ze senzoru úhlu náběhu nebo z počítače letových dat.

Je výhodné, když člen pro hmatové zprostředkování informací obsahuje alespoň dva klouby pro změnu míry asymetrie.

Systém spojený s hlavicí řídicí páky letadla ve výhodném provedení obsahuje dva servomotory. Člen pro hmatové zprostředkování informací je pomocí alespoň jednoho prvního dílu přenášejícího mechanický pohyb propojen s prvním ze servomotorů a pomocí alespoň jednoho druhého dílu přenášejícího mechanický pohyb je propojen s druhým ze servomotorů.

Je výhodné, když řídicí jednotka obsahuje jednotku pro vyhodnocení letového režimu nebo když je řídicí jednotka je s touto jednotkou pro vyhodnocení letového režimu datově propojena.

V některých provedeních jednotka pro vyhodnocení letového režimu obsahuje jednotku pro převod signálu nebo je s touto jednotkou pro převod signálu datově propojena. Jednotka pro vyhodnocení letového režimu může též obsahovat blok s informacemi o modelu letadla nebo být s tímto blokem s informacemi o modelu letadla datově propojena.

Jsou možná provedení, v nichž je jednotka pro vyhodnocení letového režimu datově propojena s alespoň jedním zdrojem informací o letových parametrech.

Je výhodné, když díly přenášející mechanický pohyb zahrnují ozubená kola a/nebo táhla.

Systém spojený s hlavicí řídicí páky letadla může dále obsahovat blok s údaji o konfiguraci letounu, přičemž tento blok s údaji o konfiguraci letounu je součástí počítače letových dat nebo má formu samostatného snímače. Tento blok s údaji o konfiguraci letounu je přímo nebo přes další součásti datově propojen s řídicí jednotkou.

Hmatová odezva má výhodu v kontinuálním předávání informace o úhlu náběhu. Systémy známé ze stavu techniky varují nebo automaticky reagují až v blízkosti pádu. Zprostředkování spojité změny úhlu náběhu funguje v širším rozsahu režimů letu a tím nejen varuje, ale funguje jako prevence proti přiblížení se nebezpečným režimům letu.

Objasnění výkresů

V obr. 1 je znázorněn boční pohled na hlavici 1 řídicí páky, ze které vyčnívá část členu 2 pro hmatové zpracování informací. Tento člen 2 pro hmatové zpracování informací se s rostoucím úhlem náběhu symetricky vysouvá a s úhlem vybočení asymetricky naklápí.

Obr. 2. zachycuje podélný řez hlavicí 1 řídicí páky vedený v rovině rovnoběžné s rovinou papíru, ve kterém je patrné umístění servomotorů 3 pro pohyb členu 2 pro hmatové zprostředkování informací i jedna z možných poloh řídicí jednotky 5.

Na obr. 3 je znázorněn mechanismus převodu rotačního pohybu ozubených kol 4 na posuvný pohyb členu 2 pro hmatové zprostředkování informací. V tomto provedení je člen 2 pro hmatové zprostředkování informací jak vysunutelný, tak i tvarově modifikovatelný s měnitelnou mírou asymetrie. Vlevo je půdorys, vpravo volné rovnoběžné promítání.

Obr 4 znázorňuje stejný mechanismus jako obr. 3, ale jsou v něm navíc znázorněny i servomotory 3, kterými je poháněn člen 2 pro hmatové zprostředkování informací. Vlevo je půdorys, vpravo volné rovnoběžné promítání.

V obr. 5a, 5b a 5c jsou znázorněny různé polohy a tvary členu 2 pro hmatové zprostředkování informací ve třech různých při různých režimech letu.

Obr. 6a a 6b ukazují příklady možností propojení mechanické části zařízení, tj. členu 2 pro hmatové zprostředkování informací, s dalšími částmi zařízení, jako jsou servomotory 3, řídicí jednotka 5 a zdroj 9 informací o letových parametrech. V obr. 6b je zakreslena varianta, v níž řídicí jednotka 5 obsahuje jednotku 6 pro vyhodnocení letového režimu. V obr. 6a je zakreslena varianta, v níž je řídicí jednotka 5 s touto jednotkou 6 pro vyhodnocení letového režimu datově propojena.

V obrázcích jsou znázorněna pouze vybraná příkladná provedení, mechanický pohon i způsoby hmatového zprostředkování informace mohou být řešeny i jinak, obdobně i elektrická část zařízení může být předmětem různých modifikací, přičemž všechna taková provedení spadají do rozsahu ochrany tohoto technického řešení tak, jak je popsáno v připojených patentových nárocích.

Příklady uskutečnění technického řešení

Systém spojený s hlavicí 1 řídicí páky letadla zprostředkovává vazbu mezi prouděním okolo křídla a pilotem a kombinuje v sobě funkci rychloměru nebo indikátoru úhlu náběhu s indikací úhlu vybočení a systému varování před pádem. Obecně používáme v této přihlášce termín zdroj 9 informací o letových parametrech. Ten může zahrnovat právě vybrané prvky ze skupiny zahrnující senzory úhlu náběhu, senzory úhlu vybočení, počítač letových dat a rychloměr a jejich kombinace. Data ze zdroje 9 informací o letových parametrech systém předává pilotovi hmatovou cestou, tedy tak, aby byla vnímána s co nejmenší zátěží pilota. Předávání informace hmatem je zajištěno členem 2 pro hmatové zprostředkování informací osazeným do hlavice 1 řídicí páky, jak je znázorněno v obr. 1.

Jak je patrné i z obr. 1 a 2 a v detailu také z obr. 4 a 5, v alespoň jedné své poloze má tento člen 2 pro hmatové zprostředkování informací část přečnívající povrch hlavice 1 řídicí páky v oblasti určené pro úchop. Tato přečnívající část přitom obsahuje alespoň jeden element, který je pohyblivý vůči povrchu hlavice 1 řídicí páky. Člen 2 pro hmatové zprostředkování informací je pomocí alespoň jednoho dílu přenášejícího mechanický pohyb propojen s alespoň jedním servomotorem 3, když tento servomotor 3 je datově propojen s řídicí jednotkou 5, která je přímo nebo přes další součásti datově propojena s alespoň jedním zdrojem 9 informací o letových parametrech. Některé možnosti tohoto propojení jsou znázorněny spolu s dalšími prvky v obr. 6a a 6b.

V obr. 6b je zakreslena varianta, v níž řídicí jednotka 5 obsahuje jednotku 6 pro vyhodnocení letového režimu. V obr. 6a je zakreslena varianta, v níž je řídicí jednotka 5 s touto jednotkou 6 pro vyhodnocení letového režimu datově propojena.

V příkladných provedeních dle obr. 6a a 6b jednotka 6 pro vyhodnocení letového režimu obsahuje jednotku 7 pro převod signálu. Jednotka 6 pro vyhodnocení letového režimu může být ale také s touto jednotkou 7 pro převod signálu datově propojena Dle obr. 6a a 6b jednotka 6 pro vyhodnocení letového režimu obsahuje též blok 8 s informacemi o modelu letadla. Jednotka 6 pro vyhodnocení letového režimu může být ale také s tímto blokem 8 s informacemi o modelu letadla datově propojena.

Vnitřní uspořádání řídicí jednotky 5 může být ale také odlišné od toho, které je zakresleno v obr. 6a a 6b. Umístění řídicí jednotky 5 je možné například přímo na hlavici 1 řídicí páky, jak je zakresleno v obr. 2, ale i kdekoli jinde dle konstrukčních možností.

Z obr. 6a a 6b je také patrné, že jednotka 6 pro vyhodnocení letového režimu může být v příkladných provedeních datově propojena s alespoň jedním zdrojem 9 informací o letových parametrech a zprostředkovávat tak ve výhodném provedení propojení řídicí jednotky 5 s tímto zdrojem 9 informací o letových parametrech. Řídicí jednotka 5 může být ale s tímto zdrojem 9 informací o letových parametrech propojena i přímo.

Pokud při změně konfigurace letounu dochází ke změně kritického úhlu náběhu je výhodné, když systém spojený s hlavicí 1 dále obsahuje blok s údaji o konfiguraci letounu. Tento blok s údaji o konfiguraci letounu, který není znázorněn v obrázcích, je součástí počítače letových dat nebo má formu samostatného snímače. Blok s údaji o konfiguraci letounu je přímo nebo přes další součásti datově propojen s řídicí jednotkou 5.

Pokud je zdroj 9 informací o letových parametrech vybrán ze skupiny obsahující senzor úhlu náběhu a počítač letových dat, člen 2 pro hmatové zprostředkování informací reaguje na tyto specifické informace o letových parametrech a za tím účelem je v oblasti určené pro úchop hlavice 1 řídicí páky alespoň částečně vysunutelný směrem vně od povrchu hlavice 1 řídicí páky, přičemž míra vysunutí je měnitelná podle údajů ze senzoru úhlu náběhu nebo z počítače letových dat.

Zdroj 9 informací o letových parametrech může být vybrán také ze skupiny obsahující senzor úhlu vybočení a počítač letových dat. Člen 2 pro hmatové zprostředkování informací reaguje na tyto specifické informace o letových parametrech a za tím účelem je v oblasti určené pro úchop hlavice 1 řídicí páky alespoň částečně tvarově modifikovatelný s měnitelnou mírou asymetrie. Míra asymetrie závisí na údajích ze senzoru úhlu vybočení nebo z počítače letových dat.

Posledně uvedené provedení lze také kombinovat s provedením, jehož popis bezprostředně přecházel. To znamená, že míra vysunutí členu 2 pro hmatové zprostředkování informací dává pilotovi informaci o úhlu náběhu a současně míra asymetrie členu 2 pro hmatové zprostředkování informací dává pilotovi informaci o úhlu vybočení.

Poloha vysunutí je pilotem vnímána jako relativní vzdálenost mezi pevnou a pohyblivou částí, tedy mezi povrchem hlavice 1 řídicí páky letadla a členem 2 pro hmatové zprostředkování informací. Relativní vzdálenost je pro přenos spojité veličiny zvolena proto, že člověk si na absolutní polohu nebo například na vibrace může snadno zvyknout a přestat ji vnímat.

V obr. 3, 4, 5a, 5b a 5c je zakresleno výhodné provedení členu 2 pro hmatové zprostředkování informací, v němž se část tohoto členu 2, která může v alespoň jedné své poloze přečnívat povrch hlavice 1 řídicí páky v oblasti určené pro úchop, vysunuje nebo mění asymetrii jako celek. To ale není podmínkou pro fungování zařízení, ekvivalentní zprostředkování hmatové informace může být při jiném konstrukčním provedení zaručeno i v případě, kdy část členu 2 pro hmatové zprostředkování informací, která může přečnívat povrch hlavice 1 řídicí páky, obsahuje alespoň jeden element, který je pohyblivý vůči povrchu hlavice 1 řídicí páky. Postačí, když se míra vysunutí nebo míra asymetrie bude měnit jen u tohoto jednoho elementu.

Technické řešení vysouvání členu 2 pro hmatové zprostředkování informací může být zajištěno jedním nebo i dvěma a více než dvěma servomotory 3. Provedení se dvěma servomotory 3 je podrobně zakresleno v obr. 4. Toto výhodné provedení umožňuje současně i změnu míry asymetrie členu 2 pro hmatové zprostředkování informací, jak je ještě lépe patrné z obr. 5.

Servomotory 3 mohou v tomto provedení pomocí ozubených kol 4 vysouvat pohyblivý člen 2 pro hmatové zprostředkování informací symetricky na základě úhlu náběhu, případně rychlosti letu, a asymetricky na základě úhlu vybočení. Servomotory jsou ovládány prostřednictvím řídicí jednotky 5 (v příkladném řešení mikrokontrolér ATMega32u4). Údaje o úhlu vysunutí jednotlivých stran výsuvného členu 2 pro hmatové zprostředkování informací jsou zprostředkovány jednotkou 6 pro vyhodnocení letového režimu, která typicky obsahuje řídicí jednotku 7 pro převod signálu (v příkladném řešení mikrokontrolér ATMega32u4) a blok 8 s informacemi o modelu daného letadla. Údaje ze zdroje 9 informací o letových parametrech jsou zpracovány jednotkou 7 pro převod signálu a s ohledem na údaje o letovém modelu daného letadla z bloku 8 přepočteny na vzdálenost vysunutí jednotlivých stran členu 2 pro hmatové zprostředkování informací.

Z obr. 3, 4 a 5 je patrné, že díly přenášející mechanický pohyb mohou zahrnovat ozubená kola 4. Díly přenášející mechanický pohyb mohou ale také zahrnovat např. táhla, jejich kombinaci s ozubenými koly apod. V obr. 3 je patrný jeden z možných mechanismů změny míry vysunutí a asymetrie. Pro změnu míry asymetrie člen 2 pro hmatové zprostředkování informací obsahuje alespoň dva klouby, typicky v rozích, což umožňuje nesymetrické vysouvání levé a pravé části členu 2 pro hmatové zprostředkování informací. Každá strana je poháněna jedním servomotorem 3 přes jedno ozubené kolo 4.

Je tedy výhodné, když systém obsahuje dva servomotory 3. Člen 2 pro hmatové zprostředkování informací je přitom pomocí alespoň jednoho prvního dílu přenášejícího mechanický pohyb, tj. v obr. 3 vpravo například prostřednictvím horního ozubeného kola 4, propojen s prvním ze servomotorů 3. Podobně je člen 2 pro hmatové zprostředkování informací pomocí alespoň jednoho druhého dílu přenášejícího mechanický pohyb, tj. v obr. 3 vpravo např. prostřednictvím dolního ozubeného kola 4, propojen s druhým ze servomotorů 3.

V obr. 3 vpravo vysouvá pohyb horního ozubeného kola 4 levou část členu 2 pro hmatové zprostředkování informací a pohyb dolního ozubeného kola 4 vysouvá pravou část členu 2 pro hmatové zprostředkování informací. Pokud je pohyb obou ozubených kol 4 a tedy obou bočních částí členu 2 pro hmatové zprostředkování informací synchronní, dochází k výsuvu tohoto členu 2, je-li asynchronní, dochází ke změně míry asymetrie tohoto členu 2, případně v kombinaci s jeho vysunutím, viz též obr. 5a, 5b a 5c.

V obr. 5 je zakreslen člen 2 pro hmatové zprostředkování informací v různých režimech letu. Na obr. 5a je malý úhel náběhu, na obr. 5b je velký úhel náběhu a na obr. 5c je let s vybočením.

Průmyslová využitelnost

Průmyslové využití navrženého řešení lze očekávat především ve všeobecném letectví (general aviation), kde může přispět ke zvýšení situačního povědomí pilotů a v důsledku zvýšit bezpečnost.

NÁROKY NA OCHRANU

1. Systém spojený s hlavicí řídicí páky letadla, **vyznačující se tím**, že obsahuje člen (2) pro hmatové zprostředkování informací, který je osazen do hlavice (1) řídicí páky tak, že v alespoň jedné své poloze má tento člen (2) pro hmatové zprostředkování informací část přečnívající povrch hlavice (1) řídicí páky v oblasti určené pro úchop, kde tato přečnívající část obsahuje alespoň jeden element, který je pohyblivý vůči povrchu hlavice (1) řídicí páky, přičemž člen (2) pro hmatové zprostředkování informací je pomocí alespoň jednoho dílu přenášejícího mechanický pohyb propojen s alespoň jedním servomotorem (3), když tento servomotor (3) je datově propojen s řídicí jednotkou (5), která je přímo nebo přes další součásti datově propojena s alespoň jedním zdrojem (9) informací o letových parametrech.

2. Systém spojený s hlavicí řídicí páky letadla podle nároku 1, **vyznačující se tím**, že zdroje (9) informací o letových parametrech jsou vybrány ze skupiny obsahující senzor úhlu náběhu, senzor úhlu vybočení, počítač letových dat.

3. Systém spojený s hlavicí řídicí páky letadla podle nároku 1 nebo 2, **vyznačující se tím**, že zdroj (9) informací o letových parametrech je vybrán ze skupiny obsahující senzor úhlu náběhu a počítač letových dat, přičemž člen (2) pro hmatové zprostředkování informací je v oblasti určené pro úchop hlavice (1) řídicí páky alespoň částečně vysunutelný směrem vně od povrchu hlavice (1) řídicí páky, přičemž míra vysunutí je měnitelná podle údajů ze senzoru úhlu náběhu nebo z počítače letových dat.

4. Systém spojený s hlavicí řídicí páky letadla podle kteréhokoli z nároků 1 až 3, **vyznačující se tím**, že zdroj (9) informací o letových parametrech je vybrán ze skupiny obsahující senzor úhlu vybočení a počítač letových dat, přičemž člen (2) pro hmatové zprostředkování informací je v oblasti určené pro úchop hlavice (1) řídicí páky alespoň částečně tvarově modifikovatelný s měnitelnou mírou asymetrie podle údajů ze senzoru úhlu vybočení nebo z počítače letových dat.

5. Systém spojený s hlavicí řídicí páky letadla podle nároku 4, **vyznačující se tím**, že člen (2) pro hmatové zprostředkování informací obsahuje alespoň dva klouby pro změnu míry asymetrie.

6. Systém spojený s hlavicí řídicí páky letadla podle kteréhokoli z nároků 1 až 5, **vyznačující se tím**, že obsahuje dva servomotory (3), přičemž člen (2) pro hmatové zprostředkování informací je pomocí alespoň jednoho prvního dílu přenášejícího mechanický pohyb propojen s prvním ze servomotorů (3) a pomocí alespoň jednoho druhého dílu přenášejícího mechanický pohyb je propojen s druhým ze servomotorů (3).

7. Systém spojený s hlavicí řídicí páky letadla podle kteréhokoli z nároků 1 až 6, **vyznačující se tím**, že řídicí jednotka (5) obsahuje jednotku (6) pro vyhodnocení letového režimu nebo že řídicí jednotka (5) je s touto jednotkou (6) pro vyhodnocení letového režimu datově propojena.

8. Systém spojený s hlavicí řídicí páky letadla podle nároku 7, **vyznačující se tím**, že jednotka (6) pro vyhodnocení letového režimu obsahuje jednotku (7) pro převod signálu nebo je s touto jednotkou (7) pro převod signálu datově propojena a že jednotka (6) pro vyhodnocení letového režimu obsahuje též blok (8) s informacemi o modelu letadla nebo je s tímto blokem (8) s informacemi o modelu letadla datově propojena.

9. Systém spojený s hlavicí řídicí páky letadla podle nároku 7 nebo 8, **vyznačující se tím**, že jednotka (6) pro vyhodnocení letového režimu je datově propojena s alespoň jedním zdrojem (9) informací o letových parametrech.

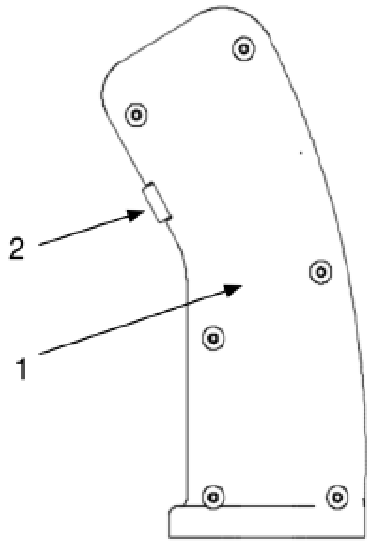
10. Systém spojený s hlavicí řídicí páky letadla podle kteréhokoli z nároků 1 až 9, **vyznačující se tím**, že díly přenášející mechanický pohyb zahrnují ozubená kola (4) a/nebo táhla.

11. Systém spojený s hlavicí řídicí páky letadla podle kteréhokoli z nároků 1 až 9, **vyznačující se tím**, že dále obsahuje blok s údaji o konfiguraci letounu, přičemž tento blok s údaji o konfiguraci letounu je součástí počítače letových dat nebo má formu samostatného snímače a přičemž blok s údaji o konfiguraci letounu je přímo nebo přes další součásti datově propojen s řídicí jednotkou (5).

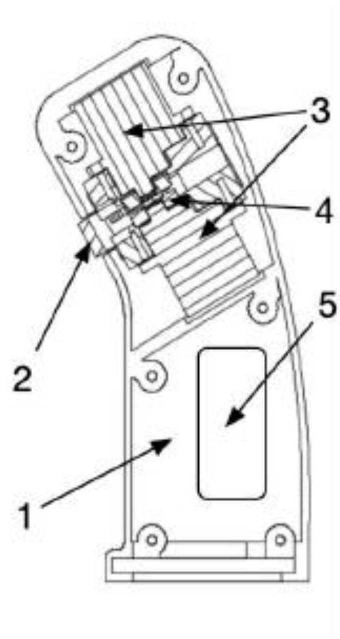
4 výkresy

Seznam vztahových značek:

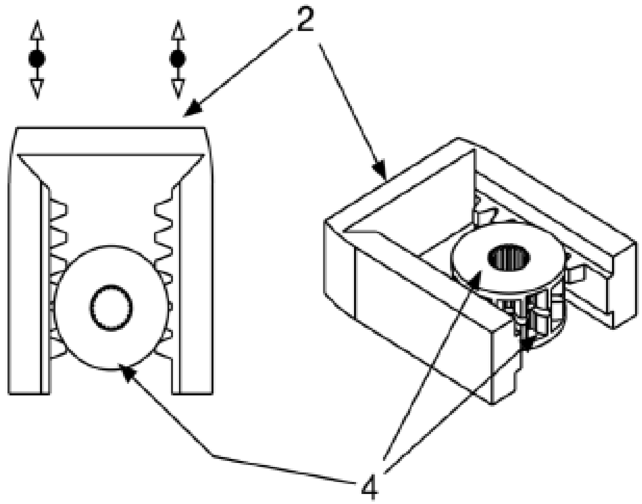
1 – hlavice řídicí páky
2 – člen pro hmatové zprostředkování informací
3 – servomotor
4 – ozubená kola
5 – řídicí jednotka
6 – jednotka pro vyhodnocení letového režimu
7 – jednotka pro převod signálu
8 – blok s informacemi o modelu letadla
9 – zdroj informací o letových parametrech.



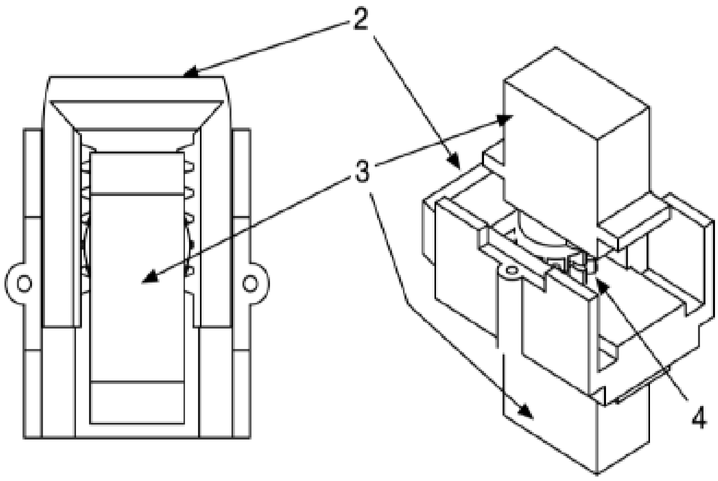
Obr. 1



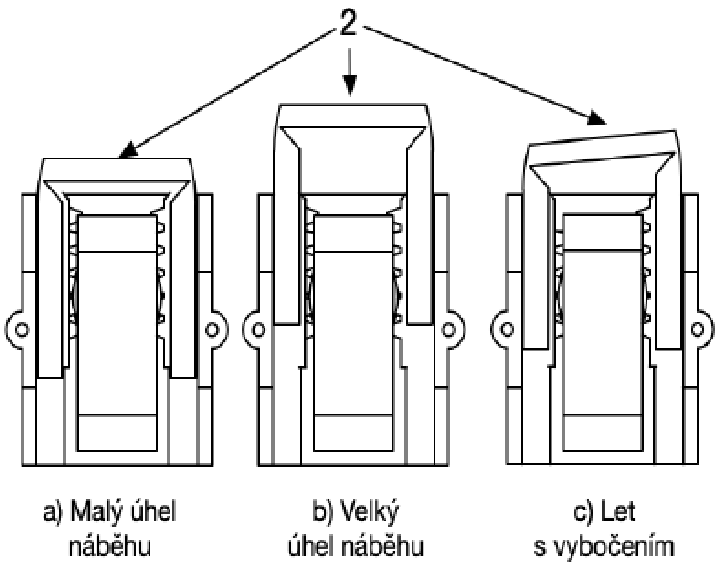
Obr. 2



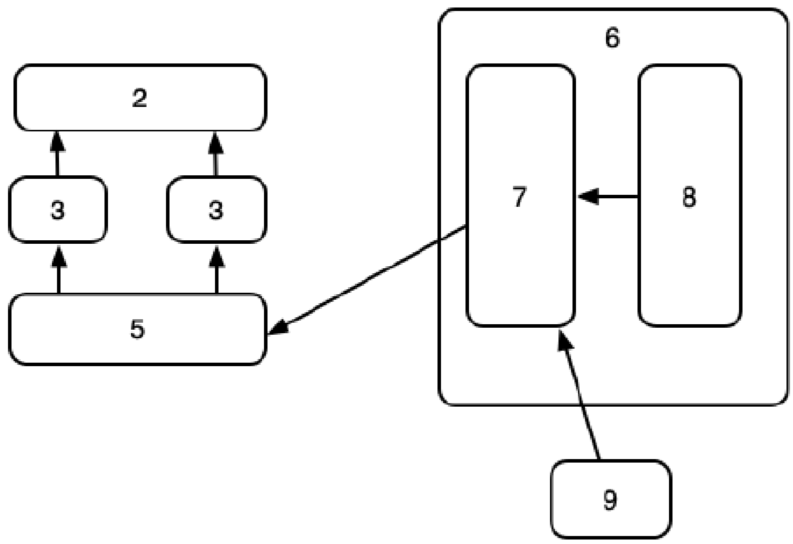
Obr. 3



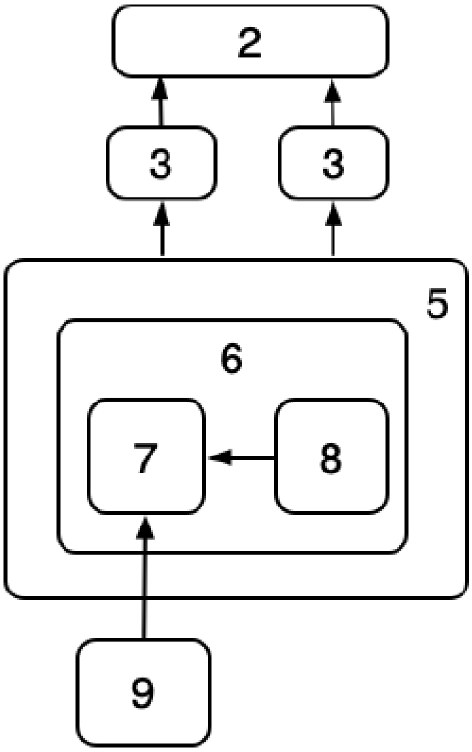
Obr. 4


2
a) Malý úhel náběhu
b) Velký úhel náběhu
c) Let s vybočením

Obr. 5


2
3
3
5
6
7
8
9

Obr. 6a



Obr. 6b

UŽITNÝ VZOR

(11) Číslo dokumentu:
33 800
(13) Druh dokumentu: **U1**
(51) Int. Cl.:
B60T 17/18 (2006.01)

(19) ČESKÁ REPUBLIKA

ÚŘAD PRŮMYSLOVÉHO VLASTNICTVÍ

(21) Číslo přihlášky: **2019-36949**
(22) Přihlášeno: **02.12.2019**
(47) Zapsáno: **27.02.2020**

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Systém pro zprostředkování informací pomocí vibrací pro zachování bezpečného režimu letu spojený s pedály nožního řízení letadla

CZ 33800 U1

Systém pro zprostředkování informací pomocí vibrací pro zachování bezpečného režimu letu spojený s pedály nožního řízení letadla

Oblast techniky

Hmatové zprostředkování informací pro zachování bezpečného režimu letu řeší problém, kdy může dojít ke ztrátě ovladatelnosti letadla v důsledku překročení maximálního úhlu náběhu (letadlo přejde do režimu pádu). Ještě nebezpečnější situace nastává při současném vybočení (letadlo může přejít do vývrtky nebo do pádu po křídle). Pokud k takové situaci dojde v blízkosti země, zejména po vzletu nebo při přiblížení, mohou být následky fatální.

Dosavadní stav techniky

Letadla jsou vybavena rychloměry, které vizuální cestou informují pilota o rychlosti letu a v dnešní době i často systémy varování před pádem, které buď vizuálně nebo zvukově varují pilota, při přiblížení se kritickému úhlu náběhu. Dopravní a vojenské letouny bývají vybavené i indikací úhlu náběhu (anglicky Angle of Attack, ve zkratce AoA), která je z pohledu pilotáže a případné ztráty rychlosti a řiditelnosti důležitější než klasický rychloměr.

Nevýhodou vizuální indikace rychlosti (rychloměr), vybočení (příčný relativní sklonoměr) a úhlu náběhu (indikátor úhlu náběhu) je, že zpravidla vyžadují vědomé odečítání prostřednictvím tzv. centrálního vidění. V takovém případě pilot musí věnovat značnou část pozornosti odečítání hodnot na těchto přístrojích. V případě letů za viditelnosti (VFR) a v blízkosti země musí pilot současně věnovat maximum pozornosti situaci v okolí (zachování situačního povědomí, dodržení odstupu od překážek a ostatních letadel).

Nevýhodou zvukových varování o blížícím se překročení maximálního úhlu náběhu je relativně krátká časová prodleva, pokud tato situace nastává příliš rychle. Zároveň zvukové varování nezprostředkovává informaci o případném úhlu vybočení (anglicky Angle of Slip, ve zkratce AoS). Další nevýhodou je možná interference z dalšími zdroji zvuku (komunikace prostřednictvím rádia, hovor v kabině, hluk motoru).

Větší letouny bývají standardně vybaveny systémy shaker a pusher. Shaker vibracemi varuje před přiblížením k pádu, pokud pilot nezareaguje, pusher potlačí sám řízení, čímž dojde k úpravě trajektorie letu směrem ke klesání a zvýšení rychlosti letu. Nevýhodou systémů typu shaker je relativně krátká časová prodleva, zejména při rychlé změně úhlu náběhu. Tyto systémy také neposkytují informaci o úhlu vybočení. Nevýhodou systémů pusher je jejich komplexnost a s tím spojená možnost vyšší poruchovosti a také vysoká cena.

Podstata technického řešení

Některé výše uvedené nedostatky odstraňuje systém spojený s pedály nožního řízení letadla podle předkládaného technického řešení, který umožňuje předávání informace o úhlu náběhu (AoA) a úhlu vybočení (AoS) prostřednictvím hmatu. Podstatou tohoto systému je, že na každém z pedálů nožního řízení letadla je v oblasti určené pro kontakt s nohou pilota umístěn alespoň jeden člen pro zprostředkování informací pomocí vibrací. Každý tento člen je mechanicky propojen se svým vlastním vibračním motorem, který je umístěn na tomtéž pedálu jako jemu příslušný člen pro zprostředkování informací pomocí vibrací. Každý vibrační motor je přitom datově propojen s řídicí jednotkou, která je přímo nebo přes další součásti datově propojena s alespoň jedním zdrojem informací o letových parametrech.

V jednom výhodném provedení je alespoň jeden člen pro zprostředkování informací pomocí vibrací od pedálu nožního řízení letadla alespoň částečně mechanicky odizolován flexibilním materiálem pro tlumení vibrací.

Zdroje informací o letových parametrech jsou s výhodou vybrány ze skupiny obsahující senzor úhlu náběhu nebo senzory úhlu náběhu, senzor úhlu vybočení nebo senzory úhlu vybočení, počítač letových dat a jejich kombinace.

Je výhodné, když je na každém z pedálů nožního řízení letadla umístěn alespoň jeden vibrační motor, který má nastavitelný alespoň jeden z parametrů vibrací vybraný ze skupiny frekvence, amplituda, délka vibračního pulzu, délka pauzy mezi vibračními pulzy.

Je možné provedení, v němž je zdroj informací o letových parametrech je vybrán ze skupiny obsahující senzor úhlu náběhu nebo senzory úhlu náběhu, počítač letových dat a jejich kombinace, přičemž alespoň jeden parametr vibrací je u alespoň dvou vibračních motorů umístěných na různých pedálech nožního řízení letadla řídicí jednotkou nastavitelný současně a shodně podle údajů ze zdroje informací o letových parametrech.

Zdroj informací o letových parametrech může být také vybrán ze skupiny obsahující senzor úhlu vybočení nebo senzory úhlu vybočení, počítač letových dat a jejich kombinace, přičemž alespoň jeden parametr vibrací alespoň jednoho vibračního motoru umístěného na jednom pedálu nožního řízení letadla je řídicí jednotkou nastavitelný podle údajů ze zdroje informací o letových parametrech odlišně, než tentýž parametr vibrací alespoň jednoho vibračního motoru umístěného na druhém pedálu nožního řízení letadla.

Je výhodné, když jsou alespoň některé parametry vibrací alespoň některých vibračních motorů nastavitelné pilotem.

Je rovněž výhodné, je-li alespoň jeden parametr vibrací alespoň jednoho vibračního motoru umístěného na jednom pedálu nožního řízení letadla pilotem nastavitelný nezávisle na stejném parametru vibrací alespoň jednoho vibračního motoru umístěného na druhém pedálu nožního řízení letadla.

Je možné provedení, v němž řídicí jednotka obsahuje jednotku pro vyhodnocení letového režimu, nebo v němž je řídicí jednotka s touto jednotkou pro vyhodnocení letového režimu propojena.

Jednotka pro vyhodnocení letového režimu může obsahovat jednotku pro převod signálu nebo být s touto jednotkou pro převod signálu propojena. Jednotka pro vyhodnocení letového režimu může obsahovat též blok s informacemi o modelu letadla, nebo být s tímto blokem s informacemi o modelu letadla propojena.

Jednotka pro vyhodnocení letového režimu je s výhodou datově propojena s alespoň jedním zdrojem informací o letových parametrech.

Je výhodné, když systém dále obsahuje blok s údaji o konfiguraci letadla, přičemž tento blok s údaji o konfiguraci letadla je součástí počítače letových dat nebo má formu samostatného snímače. Blok s údaji o konfiguraci letadla je přímo nebo prostřednictvím dalších dílů propojen s řídicí jednotkou.

Hmatová odezva pomocí vibrací v systému dle předkládaného technického řešení má výhodu ve vyvolání intuitivní správné reakce.

Objasnění výkresů

V obr. 1 je představen příklad umístění členů 2 pro zprostředkování informací pomocí vibrací v jednom z pedálů 1 nožního řízení letadla pro plochý typ pedálu

Obr. 2 představuje příklad jiného možného provedení členů 2 pro zprostředkování informací pomocí vibrací v jednom z pedálů 1 nožního řízení letadla pro tyčový typ pedálu

Na obr. 3 je ukázka provedení členu 2 pro zprostředkování informací pomocí vibrací v jednom z pedálů 1 nožního řízení letadla pro plochý typ pedálu

Obr. 4 představuje jednu z možných variant propojení jednotek systému pro zprostředkování informací o úhlu náběhu a úhlu vybočení pomocí členů 2 pro zprostředkování informací pomocí vibrací na pedálech 1 nožního řízení.

Obr. 5 představuje jinou variantu propojení jednotek systému pro zprostředkování informací o úhlu náběhu a úhlu vybočení pomocí členů 2 pro zprostředkování informací pomocí vibrací na pedálech 1 nožního řízení.

Obr. 6 představuje ukázku parametrů vibrací členů 2 pro zprostředkování informací pomocí vibrací, jimiž jsou zprostředkovány informace o letových parametrech. Nesymetrická signalizace je znázorněna pro případ potřeby sešlápnutí levého pedálu.

Příklady uskutečnění technického řešení

Systém spojený s pedály 1 nožního řízení letadla zprostředkovává vazbu mezi prouděním okolo křídla a pilotem a kombinuje v sobě funkci rychloměru nebo indikátoru úhlu náběhu s indikací úhlu vybočení a systému varování před pádem. Obecně používáme v tomto textu termín zdroj 9 informací o letových parametrech. Ten může zahrnovat vybrané prvky ze skupiny zahrnující senzor úhlu náběhu nebo více senzorů úhlu náběhu, senzor úhlu vybočení nebo více senzorů úhlu vybočení, počítač letových dat a jejich kombinace. Zdrojů 9 informací o letových parametrech může být i více. Data ze zdroje 9 informací o letových parametrech nebo ze zdrojů 9 informací o letových parametrech systém předává pilotovi hmatovou cestou pomocí vibrací, tedy tak, aby byla vnímána s co nejmenší zátěží pilota. Předávání informace hmatem je zajištěno členy 2 pro zprostředkování informací pomocí vibrací, osazenými do pedálů 1 nožního řízení, jak je znázorněno v obr. 1 a 2.

Detail jednoho možného provedení členu 2 pro zprostředkování informací pomocí vibrací pro případ plochého pedálu 1 je ukázán v obr. 3.

Jak je patrné i z obr. 1 a 2, člen 2 nebo členy 2 pro zprostředkování informací pomocí vibrací, jsou umístěny v částech pedálů nožního řízení určených ke kontaktu s nohou pilota. Na každém z pedálů 1 nožního řízení letadla je umístěn alespoň jeden člen 2 pro zprostředkování informací pomocí vibrací, přičemž každý tento člen 2 je mechanicky propojen se svým vlastním vibračním motorem 4, který je umístěn na tomtéž pedálu jako jemu příslušný člen 2 pro zprostředkování informací pomocí vibrací. Každý vibrační motor 4 je přitom datově propojen s řídicí jednotkou 5, která je přímo nebo přes další součásti datově propojena s alespoň jedním zdrojem 9 informací o letových parametrech. Některé možnosti tohoto propojení jsou znázorněny spolu s dalšími prvky v obr. 4 a 5.

V obr. 4 je zakreslena varianta, v níž řídicí jednotka 5 obsahuje jednotku 6 pro vyhodnocení letového režimu.

V obr. 5 je zakreslena varianta, v níž je řídicí jednotka 5 s touto jednotkou 6 pro vyhodnocení letového režimu propojena.

V příkladných provedeních dle obr. 4, 5 jednotka 6 pro vyhodnocení letového režimu obsahuje jednotku 7 pro převod signálu. Může být ale také s touto jednotkou 7 pro převod signálu propojena. Jednotka 6 pro vyhodnocení letového režimu obsahuje též blok 8 s informacemi o modelu letadla. Může být ale také s tímto blokem 8 s informacemi o modelu letadla propojena.

Vnitřní uspořádání řídicí jednotky 5 může být ale také odlišné od toho, které je zakresleno v obr. 4, 5. Umístění řídicí jednotky 5 je možné kdekoli dle konstrukčních možností.

Z obr. 4, 5 je také patrné, že jednotka 6 pro vyhodnocení letového režimu může být v příkladných provedeních datově propojena s alespoň jedním zdrojem 9 informací o letových parametrech.

Je výhodné, když systém spojený s pedály 1 nožního řízení letadla dále obsahuje blok s údaji o konfiguraci letadla. Tento blok s údaji o konfiguraci letadla, který není znázorněn v obrázcích, je součástí počítače letových dat nebo má formu samostatného snímače. Blok s údaji o konfiguraci letadla je přímo nebo prostřednictvím dalších dílů propojen s řídicí jednotkou 5.

Ve výhodných provedeních je alespoň jeden člen 2 pro zprostředkování informací pomocí vibrací od pedálu 1 nožního řízení letadla alespoň částečně mechanicky odizolován flexibilním materiálem 3 pro tlumení vibrací. Díky tomu je omezen přenos vibrací z jednoho pedálu na druhý. Toto provedení je znázorněno v obr. 1 a obr. 2.

Je výhodné, když je na každém z pedálů 1 nožního řízení letadla je alespoň jeden vibrační motor 4 uzpůsobený tak, že má nastavitelný alespoň jeden z parametrů vibrací vybraný ze skupiny frekvence, amplituda, délka vibračního pulzu, délka pauzy mezi vibračními pulzy. Příklad nastavitelných parametrů vibrací jsou znázorněny v obr. 6 pro pravý i levý pedál. Jde samozřejmě jen o jeden z mnoha možných příkladů, frekvence, amplitudy, délky vibračního pulzu i délky pauzy mezi vibračními pulzy se mohou měnit jak podle údajů ze zdrojů informací 9 o letových parametrech, tak podle uživatelského nastavení. Frekvencí je myšlena frekvence kmitů v rámci pulzu. Frekvence může být provázána s amplitudou a nastavena manuálně na určitou hodnotu. Délky pulzů, pauz a symetrie či asymetrie mezi levým a pravým pedálem mohou zprostředkovávat informace o letových parametrech. K tomuto zprostředkování lze případně využít i amplitudu a frekvenci vibrací.

Zdroj 9 informací o letových parametrech může být vybrán ze skupiny obsahující senzor úhlu náběhu nebo senzory úhlu náběhu, počítač letových dat a jejich kombinace. V tomto případě je výhodné, když systém spojený s pedály 1 nožního řízení pro zprostředkování informací pomocí vibrací poskytuje informaci o úhlu náběhu prostřednictvím vibrací obou pedálů současně. Způsob vibrací je měnitelný podle údajů ze senzoru úhlu náběhu nebo z počítače letových dat, z něhož jsou typicky vybírány takové informace, které se týkají úhlu náběhu nebo z nichž lze úhel náběhu dopočíst. Alespoň jeden parametr vibrací je pak u alespoň dvou vibračních motorů 4 umístěných na různých pedálech 1 nožního řízení letadla řídicí jednotkou 5 nastavitelný současně a shodně podle údajů ze zdroje 9 informací o letových parametrech. Ve výhodném provedení pak oba pedály obsahují totožné členy 2 pro zprostředkování informací pomocí vibrací totožně rozmístěné na obou pedálech. Pro signalizaci úhlu náběhu pak členy 2 pro zprostředkování informací pomocí vibrací umístěné na pravém pedálu vibrují stejně jako členy 2 pro zprostředkování informací pomocí vibrací umístěné na levém pedálu. Příklad této situace je znázorněn v levé části obr. 6 jako symetrická signalizace. Rostoucí úhel náběhu je typicky signalizován pomocí zvyšující se délky pulzu vibrací případně zkracováním pauzy mezi pulzy na obou pedálech současně.

Zdroj 9 informací o letových parametrech může být také vybrán ze skupiny obsahující senzor úhlu vybočení nebo senzory úhlu vybočení, počítač letových dat a jejich kombinace. Z počítače letových dat jsou přitom typicky vybírány takové informace, které se týkají úhlu vybočení nebo ze kterých lze úhel vybočení dopočíst. V tom případě je alespoň jeden parametr vibrací alespoň jednoho vibračního motoru 4 umístěného na jednom pedálu 1 nožního řízení letadla řídicí jednotkou 5 nastavitelný podle údajů ze zdroje 9 informací o letových parametrech odlišně než tentýž parametr vibrací alespoň jednoho vibračního motoru 4 umístěného na druhém pedálu 1 nožního řízení letadla. V tomto provedení mohou být tedy parametry vibrací vibračních motorů 4 umístěných na různých pedálech 1 nožního řízení letadla rozdílné. Alespoň některé členy 2 pro zprostředkování informací pomocí vibrací na pravém pedálu pak vibrují jinak než alespoň některé členy 2 pro zprostředkování informací pomocí vibrací na levém pedálu, přičemž míra asymetrie těchto vibrací závisí na údajích ze senzoru úhlu vybočení a/nebo z počítače letových dat. Rostoucí asymetrie vibrací na levém a pravém pedálu pak přináší informaci o rostoucím úhlu vybočení. Rostoucí asymetrie se může projevovat např. délkou pulzů vibrací na pedálu, jehož sešlápnutím dojde ke snížení úhlu vybočení. Jeden příklad vibrací signalizujících rostoucí úhel vybočení je znázorněn v pravé části obr. 6 jako nesymetrická signalizace.

Posledně uvedené provedení lze také kombinovat s provedením, jehož popis bezprostředně předcházel. To znamená, že některý nebo některé z parametrů vibrací členů 2 pro zprostředkování informací pomocí vibrací, které jsou symetrické na obou pedálech, dávají pilotovi informaci o úhlu náběhu. Současně pak ty parametry vibrací členů 2 pro zprostředkování informací pomocí vibrací, které jsou v levém pedálu jiné než v pravém pedálu a poskytují tedy asymetrický vjem, dávají pilotovi informaci o úhlu vybočení. Tento případ lze signalizovat např. tak, že se budou střídat časové úseky, v nichž jsou vibrace členů 2 v obou pedálech 1 navzájem symetrické, což podává informaci o úhlu náběhu, s časovými úseky, v nichž jsou naopak vibrace členů 2 v pravém pedálu 1 nesymetrické vůči vibracím v levém pedálu 1, což podává informaci o úhlu vybočení. Systém počítá i s osobním nastavením: Je výhodné, když jsou alespoň některé parametry vibrací alespoň některých vibračních motorů 4 jsou nastavitelné pilotem. Pilot si tak může podle své vlastní citlivosti, obuvi apod. nastavit např. vhodnou amplitudu nebo frekvenci vibrací.

Výhodné také je, když je alespoň jeden parametr vibrací alespoň jednoho vibračního motoru 4 umístěného na jednom pedálu 1 nožního řízení letadla pilotem nastavitelný nezávisle na stejném parametru vibrací alespoň jednoho vibračního motoru 4 umístěného na druhém pedálu 1 nožního řízení letadla.

Předkládané technické řešení tedy umožňuje pilotovi intuitivně reagovat na změny úhlu náběhu projevující se symetrickými vibracemi obou pedálů 1 i na změny úhlu vybočení projevující se nesymetrickými vibracemi.

Průmyslová využitelnost

Průmyslové využití navrženého řešení lze očekávat především ve všeobecném letectví (general aviation), kde může přispět ke zvýšení situačního povědomí pilotů a v důsledku zvýšit bezpečnost.

NÁROKY NA OCHRANU

1. Systém pro zprostředkování informací pomocí vibrací pro zachování bezpečného režimu letu spojený s pedály nožního řízení letadla, **vyznačující se tím**, že na každém z pedálů (1) nožního řízení letadla je v oblasti určené pro kontakt s nohou pilota umístěn alespoň jeden člen (2) pro zprostředkování informací pomocí vibrací, přičemž každý tento člen (2) je mechanicky propojen se svým vlastním vibračním motorem (4), který je umístěn na tomtéž pedálu jako jemu příslušný člen (2) pro zprostředkování informací pomocí vibrací, když každý vibrační motor (4) je datově propojen s řídicí jednotkou (5), která je přímo nebo přes další součásti datově propojena s alespoň jedním zdrojem (9) informací o letových parametrech.

2. Systém podle nároku 1, **vyznačující se tím**, že alespoň jeden člen (2) pro zprostředkování informací pomocí vibrací je od pedálu (1) nožního řízení letadla alespoň částečně mechanicky odizolován flexibilním materiálem (3) pro tlumení vibrací.

3. Systém podle nároku 1 nebo 2, **vyznačující se tím**, že zdroje (9) informací o letových parametrech jsou vybrány ze skupiny obsahující senzor úhlu náběhu nebo senzory úhlu náběhu, senzor úhlu vybočení nebo senzory úhlu vybočení, počítač letových dat a jejich kombinace.

4. Systém podle kteréhokoli z nároků 1 až 3, **vyznačující se tím**, že na každém z pedálů (1) nožního řízení letadla je alespoň jeden vibrační motor (4), který má nastavitelný alespoň jeden z parametrů vibrací vybraný ze skupiny frekvence, amplituda, délka vibračního pulzu, délka pauzy mezi vibračními pulzy.

5. Systém podle nároku 4, **vyznačující se tím**, že zdroj (9) informací o letových parametrech je vybrán ze skupiny obsahující senzor úhlu náběhu nebo senzory úhlu náběhu, počítač letových dat a jejich kombinace, přičemž alespoň jeden parametr vibrací je u alespoň dvou vibračních motorů (4) umístěných na různých pedálech (1) nožního řízení letadla řídicí jednotkou (5) nastavitelný současně a shodně podle údajů ze zdroje (9) informací o letových parametrech.

6. Systém podle nároku 4 nebo 5, **vyznačující se tím**, že zdroj (9) informací o letových parametrech je vybrán ze skupiny obsahující senzor úhlu vybočení nebo senzory úhlu vybočení, počítač letových dat a jejich kombinace a alespoň jeden parametr vibrací alespoň jednoho vibračního motoru (4) umístěného na jednom pedálu (1) nožního řízení letadla je řídicí jednotkou (5) nastavitelný podle údajů ze zdroje (9) informací o letových parametrech odlišně než tentýž parametr vibrací alespoň jednoho vibračního motoru (4) umístěného na druhém pedálu (1) nožního řízení letadla.

7. Systém podle kteréhokoli z nároků 4 až 6, **vyznačující se tím**, že alespoň některé parametry vibrací alespoň některých vibračních motorů (4) jsou nastavitelné pilotem.

8. Systém podle nároku 7, **vyznačující se tím**, že alespoň jeden parametr vibrací alespoň jednoho vibračního motoru (4) umístěného na jednom pedálu (1) nožního řízení letadla je pilotem nastavitelný nezávisle na stejném parametru vibrací alespoň jednoho vibračního motoru (4) umístěného na druhém pedálu (1) nožního řízení letadla.

9. Systém podle kteréhokoli z nároků 1 až 8, **vyznačující se tím**, že řídicí jednotka (5) obsahuje jednotku (6) pro vyhodnocení letového režimu, nebo že řídicí jednotka (5) je s touto jednotkou (6) pro vyhodnocení letového režimu propojena.

10. Systém podle nároku 9, **vyznačující se tím**, že jednotka (6) pro vyhodnocení letového režimu obsahuje jednotku (7) pro převod signálu, nebo je s touto jednotkou (7) pro převod signálu propojena, a že jednotka (6) pro vyhodnocení letového režimu obsahuje též blok (8) s informacemi o modelu letadla, nebo je s tímto blokem (8) s informacemi o modelu letadla propojena.

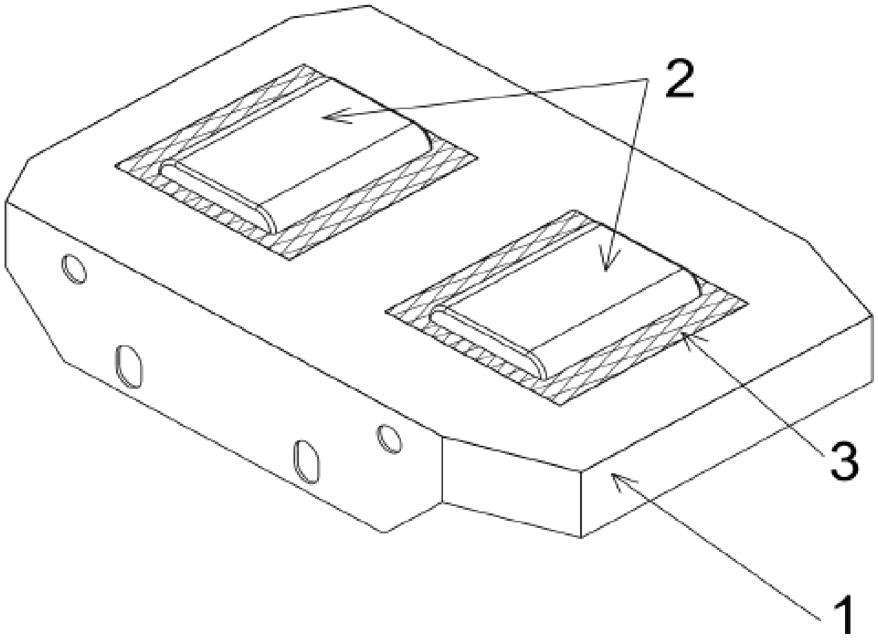
11. Systém podle nároku 9 nebo 10, **vyznačující se tím**, že jednotka (6) pro vyhodnocení letového režimu je datově propojena s alespoň jedním zdrojem (9) informací o letových parametrech.

12. Systém podle kteréhokoli z nároků 1 až 11, **vyznačující se tím**, že dále obsahuje blok s údaji o konfiguraci letadla, přičemž tento blok s údaji o konfiguraci letadla je součástí počítače letových dat, nebo má formu samostatného snímače, a přičemž blok s údaji o konfiguraci letadla je přímo nebo prostřednictvím dalších dílů propojen s řídicí jednotkou (5).

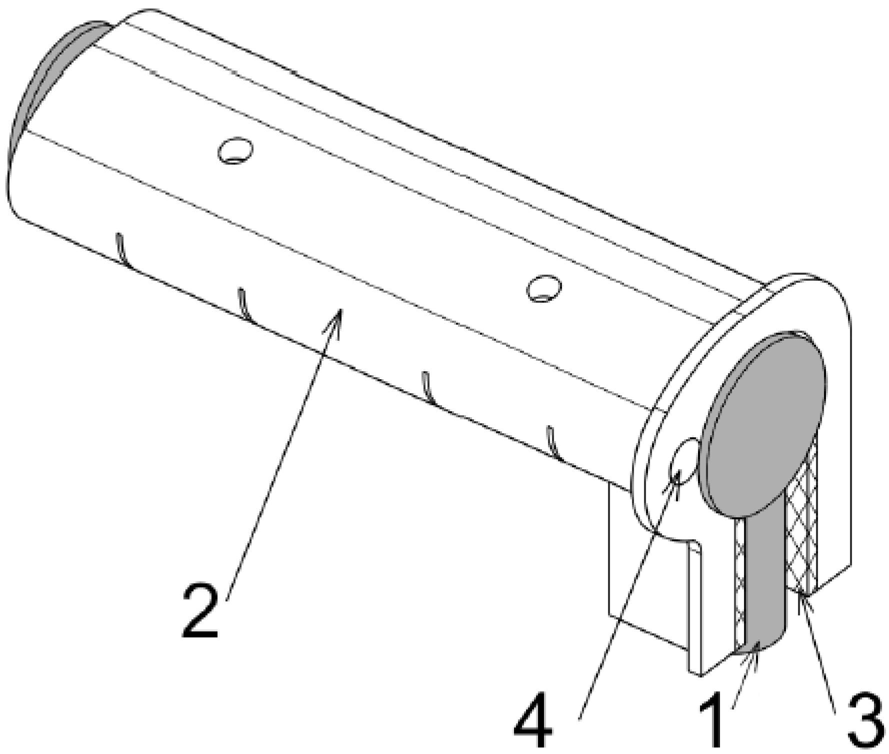
3 výkresy

Seznam vztahových značek:

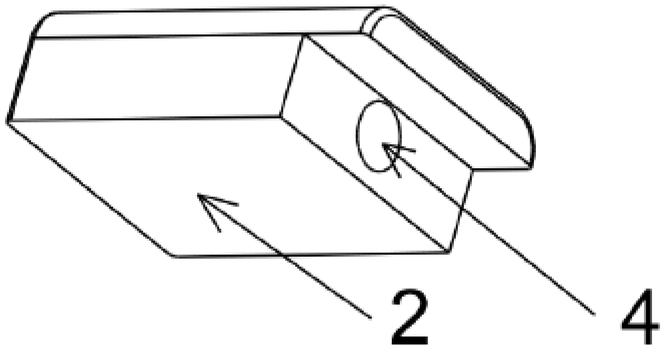
1 – pedál
2 – člen pro zprostředkování informací pomocí vibrací
3 – materiál pro tlumení vibrací
4 – vibrační motor
5 – řídicí jednotka
6 – jednotka pro vyhodnocení letového režimu
7 – jednotka pro převod signálu
8 – blok s informacemi o modelu letadla
9 – zdroj informací o letových parametrech.



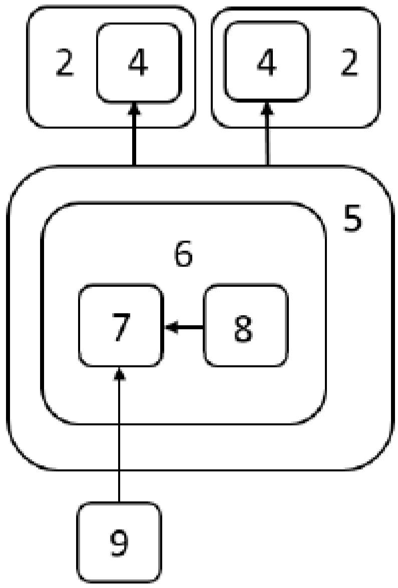
Obr. 1



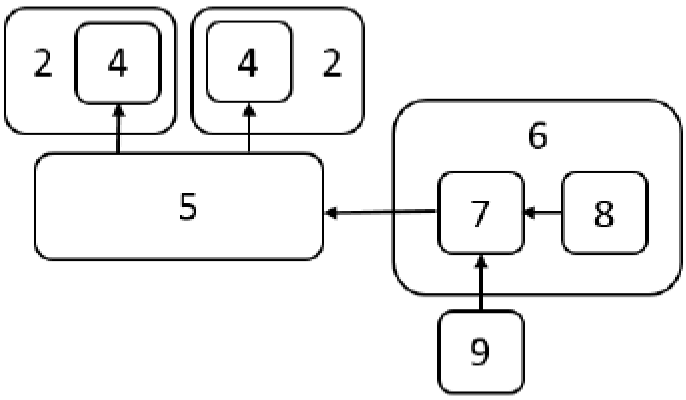
Obr. 2



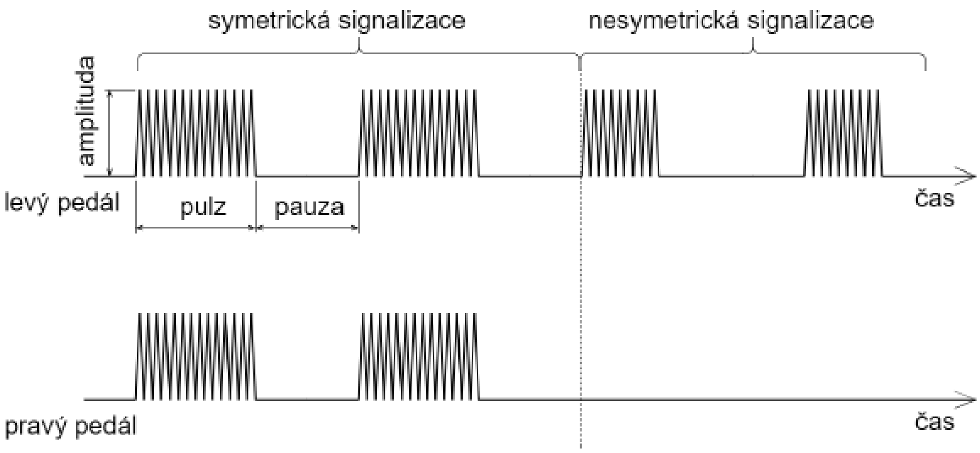
Obr. 3



Obr. 4



Obr. 5


symetrická signalizace
nesymetrická signalizace
amplituda
levý pedál
pulz
pauza
čas
pravý pedál
čas

Obr. 6

Pilot-aircraft haptic feedback tests

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Abstract

Purpose – The purpose of this study is to lead to an improvement in pilot-aircraft interaction. The goal of the performed tests is an assessment of haptic feedback, which mediates flight parameters to the pilot. Pedals indicate side-slip angle by vibrations, whereas a sliding element inside the control stick is able to continuously indicate both angles of attack and side-slip.

Design/methodology/approach – Haptic feedback applied on rudder pedals and control stick were tested on a flight simulator and flight tests in a couple of tasks. Pilot workload, readability of feedback and side-slip were then evaluated when the flight was turning.

Findings – As a useful instrument for aircraft control, haptic feedback was assessed. The feedback settings were then individually perceived, and haptic feedback slightly improved side-slip while turning in a flight test; however, the results are not statistically significant.

Practical implications – The tests provided promising results for human pilot performance. The training phase and personal settings of haptic feedback is an approach for improving the performance of human pilots.

Originality/value – The designed and tested device is a unique tool for improving pilot-aircraft interaction. This study brings valuable experiences from its flight simulator and in-flight tests.

Peer review – The peer review history for this article is available at: https://publons.com/publon/10.1108/AEAT-12-2019-0265/

Keywords Flight test, Flight simulator, Haptic feedback, Pilot-aircraft interaction

Paper type Research paper

Nomenclature

Definitions, acronyms and abbreviations

AoA = Angle of Attack;
AoS = Angle of Side-slip; and
HF = Haptic Feedback.

Introduction

The performance of human pilots lags behind that of autopilots and birds. What is the reason that computers and nature are better in flight control compared to man? The weakest chain segment of aircraft control is pilot-aircraft interaction, which is connected to all accidents of small aircraft because of a human factor. Similar to how a man feels on the ground while walking, birds feel aerodynamic characteristics of flow around their wings naturally. Many times, every minute of flight, autopilots are fed by flight parameters. Both birds and autopilots control flight with the permanent knowledge of flight parameters such as speed or dynamic pressure, angle of attack and altitude. A pilot can read all parameters on the instrumental board; however, it is out of the human ability to perceive and process all-important values during the critical phases of flight. Aircraft gives feedback such as control stick force or aircraft structure vibrations which a pilot feels without conscious instrument checking. This feedback is not sufficient by itself. As per aircraft accident statistics (EASA, 2018, NTSB, 2017), loss of control and human factor are the most common accident reasons in the general aviation sector.

The literature survey (Zikmund *et al.*, 2018) shows that the current pilot-aircraft interaction methods have certain limitations. In certain flight phases, visual sense might be overloaded. The research suggests transferring certain pilot stimuli to the haptic sense. In this study, a device that mediates flight parameters to a pilot in a haptic manner was designed and tested. The goal is to improve pilot performance for small aircrafts without an autopilot. The device comprises active elements at the control stick and rudder pedals. The angles of attack and side-slip are mediated to a pilot by vibrations of

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Aircraft Engineering and Aerospace Technology
92/9 (2020) 1407–1412

[DOI 10.1108/AEAT-12-2019-0265]

This research has been supported primarily by TACR, project no. TJ01000122 "Haptic feedback of assistant systems for flight safety improvement" and partially by the Research Center for Informatics project CZ.02.1.01/0.0/0.0/16 019/0000765.

Received 30 December 2019
Revised 29 February 2020
Accepted 7 March 2020

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rudder pedals and movements of a sliding element mounted on a control stick handle. This device has been tested at a flight simulator ($n = 12$) and then in a flight ($n = 1$). This paper brings the results of both these experiments.

Related work

Haptic technologies are in the scope of researchers dealing with airline cockpits. One of the current research topics is designing a haptic feedback (HF) system for flight envelope exceeding protection (Van Baelen *et al.*, 2018). HF is supposed to safely help a pilot control aircraft near the borders of a flight envelope. Prinet (2016) introduced a tactile spatial guidance method for collision avoidance. Castillo and Couture (2016) reports the importance of free-eyes pilot-aircraft interaction. In futuristic aircraft cockpits, morphable and interactive controls are expected. Studies related to the pilot-aircraft interaction require a good human pilot behaviour model. Such a model with visual and tactile cues perceived from the pilot-aircraft interface is presented by Xu *et al.* (2019). The segment of general aviation aircraft has different demands from haptic technologies. Beeftink *et al.* (2018) demonstrates that HF significantly increases both primary and secondary task performance of pilots. Workload ratings are significantly lesser and head-up time increases with HF. Nieuwenhuizen and Bülthoff (2014) applied HF in personal aerial vehicle control simulation. They simulated a highway in the sky display with an aim to create an easy-to-use control interface for non-expert pilots. All mentioned resources are connected with topics of pilot's workload decrease and eyes-free pilot-aircraft interaction. According to Brock *et al.* (2015), using multiple modalities can break down the complexity of communicated information. Loomis *et al.* (2012) described multiple approaches for sensory substitution of vision from the perspective of cognitive science and neuroscience.

Flight simulator test

To assess the possible effects of the HF system on pilot performance prior to flight tests, a flight simulator test was prepared. Simulator software comprised an X-plane 11 PC flight simulator and hardware composed of a joystick and rudder pedals equipped with haptic devices, as shown in Figure 1. A sliding element was built in the joystick; the sliding element mediated AoA and Aos by symmetrical and unsymmetrical movement out of the handle surface. A range of the sliding element displacement is 8 mm and is powered by two servos with power about 2×20 N. It has also a shaker function near stall flight conditions. The rudder pedals provide pulsating vibrations when a side-slip exceeds a threshold value. To decrease aircraft side-slip, the pedals vibrate at the same side where a pilot reaction is required. The vibration motors induce vibrations having a frequency of 230 Hz +−10 per cent and an amplitude of 7 g +−10 per cent.

Twelve people with a piloting license took part in the flight simulator experiment. Before the experiment, participants were given time to familiarize themselves with the flight simulator itself and afterwards with haptic devices. The Cessna 172 flight model was used during the experiment.

The first part of the experiment required the pilots to fly three times through the set of gates, thus forming a test track at low altitude above the water level at a given range of airspeed. Each flight was conducted with a different configuration of haptic devices. One flight was with HF off, another one was with AoA feedback and AoS on the joystick feedback turned on and the last one was with the AoA feedback and AoS on the rudder pedals turned on. The sequence of these flights was assigned to each pilot by the Latin square method. The ilots were requested to fly at a low airspeed with a minimal angle of side-slip. There were no instructions about verifying the turn indicator. The goal was to let pilots fly as they are used to.

The second part of the experiment required the pilot to perform a takeoff and climb out. During the climb, the engine was made inoperable by the experiment control script without prior notice to the pilot who was then required to safely get the aircraft on the ground. Half of the participants performed this task with HF; the other half performed this task without HF.

During the experiment, participants filled the questionnaire concerning their perception of feedback, information clarity, helpfulness and unambiguity. The assessment of the experiment includes the evaluation of questionnaire answers and evaluation of flight data.

Questionnaire assessment

Participants assessed their workload during each flight on scale of 1(low) - 3(high). Their answers were averaged for flights without HF, with HF AoS on a joystick and with HF AoS on rudder pedals, i.e. 1.75, 2.33 and 2.08. The workload during flight without HF was assessed to be the lowest because of insufficient training for the HF system. Intensity, unambiguity and helpfulness of information given by HF system were assessed for flights with an active HF on the following scale:

Figure 1 Flight simulator testing setup and rudder pedals

1(too low) - 5(too high), 1(no) - 5(yes), 1(poor) - 5(high) both for information on AoA and AoS. The answers were averaged among the participants and are shown in Table I.

For evaluation of flight data, cumulative side-slip angle was calculated for each flight of each pilot to measure their performance. The cumulative side-slip angle is of a dimensionless value considering the aircraft side-slip and time during which the aircraft was experiencing the side-slip. It was expected that pilots will achieve lower cumulative side-slip in flights with active HF. T-tests were then conducted to test the null hypothesis, which mean that mean values of cumulative sideslip are identical. Both flights with HF active were compared to flights with HF inactive. The null hypothesis was not rejected on a 95 per cent confidence level in both comparisons. Therefore, the HF in this test had no positive nor negative effect on the pilots' ability to fly with minimal side-slip. The answers in the questionnaire were compared with flight data using correlation coefficients, and the correlation matrix is shown in Table II.

The correlation matrix shows a weak correlation between pilots' assessment of HF helpfulness and side-slip flight data result. The pilots who assessed the helpfulness of HF with AoS indication on joystick better had poorer cumulative sideslip. While pilots who assessed the helpfulness of HF with AoS indication on pedals had lower cumulative sideslip in practice. There is also a strong correlation between flight sim hours of participants and cumulative sideslip during all flights, which shows a high dependency of the experiment result on flight simulator environment and experiences in general.

Flight test

This chapter and partially the discussion chapter contains text published at the EASN conference (blinded) where the flight test was described in a more detailed manner. For the flight test, it was necessary to create new haptic pedal extensions because pedals in the WT-9 Dynamic aircraft used for experiment had different constructions compared to those used with the flight simulator. The pedals are shown in Figures 1 and 2. The behaviour of the system was simplified compared to the flight simulator test. The AoS threshold has a fixed value and is not changed with aircraft speed in the flight test variant. The reference element marking the maximal AoA sliding element position was added to the haptic joystick, and then the shaker function of the sliding element was removed. The system was operated by a control unit based on Arduino Mega 2560 with a data logging function; the sampling frequency was 10 Hz. Flight data were acquired from vane sensors and accelerometer and saved to an SD card in the control unit. There was no filtering of the vane signals, and the vanes were observed to be sufficiently stable in the airflow. Analog signals of AoA and AoS were converted to digital with 10-bit resolution per 360 degrees. The acceleration data has not been used for control of the haptic feedback system. This data was used only for turn's identification in the post-processing of flight data record.

The flight test of the HF system comprises a pilot's subjective assessment and data collection during 360 degrees turns. The subjective assessment was aimed at inflight verification of the HF by a test pilot. This task was repeated at various speeds within the range between a safe near-stall and the maximal speed. The pilot commented on the intensity and readability of rudder pedals vibrations in side-slip flight. There were two issues to be verified. The first was possible spreading of vibrations from one pedal to the opposite pedal. The second issue was interference between natural aircraft vibrations and vibrations of HF. The positions and function of the sliding element on the control stick were tested at the same speeds as vibrations of rudder pedals.

The second task was 360 degrees turns. The turns alternated left and right. One half was flown without the HF and the second was with the HF. To mitigate the learning effect, the he HF was alternately switched on and off each second turn. AoS was measured as a parameter for the HF system evaluation, and two hypotheses were tested. The first was that HF decreases the mean value of the sideslip angle during turning. The second was that HF decreases the sideslip angle above the vibration threshold, which was set up to 5°.

Table I Questionnaire results

	Intensity	Unambiguity	Helpfulness
The flight using HF both AoA and AoS on joystick sliding element			
AoA	2.92	3.92	3.25
AoS	2.58	3.42	3.42
The flight using HF of AoA on joystick and AoS on rudder pedals			
AoA	2.92	4.67	3.67
AoS	2.67	2.75	3.5

Table II Correlation matrix of the questionnaire and simulator test results

Correlation matrix, confidence level 90% (alpha = 0.1)

Sideslip HF off [-]	Sideslip AoS joystick [-]	Sideslip AoS pedals [-]	Pilot age [years]	Real flight hours [hrs]	Flight sim. hours [scale 0-2]	HF asist, AoS joystic [scale 1-5]	HF asisit. AoS pedals [scale 1-5]
1	0.8668	0.4113	−0.0032	−0.1893	−0.6273	0.2551	−0.1386
0.8668	1	0.5613	−0.2316	−0.3087	−0.5951	0.2565	−0.2705
0.4113	0.5613	1	0.3209	−0.1021	−0.6557	−0.0997	−0.4832
−0.0032	−0.2316	0.3209	1	0.5294	−0.2099	−0.5995	−0.2435
−0.1893	−0.3087	−0.1021	0.5294	1	0.4007	−0.3997	0.0673
−0.6273	−0.5951	−0.6557	−0.2099	0.4007	1	0.1159	0.1611
0.2551	0.2565	−0.0997	−0.5995	−0.3997	0.1159	1	0.1473
−0.1386	−0.2705	−0.4832	−0.2435	0.0673	0.1611	0.1473	1

Figure 2 Haptic feedback actuators for the flight test

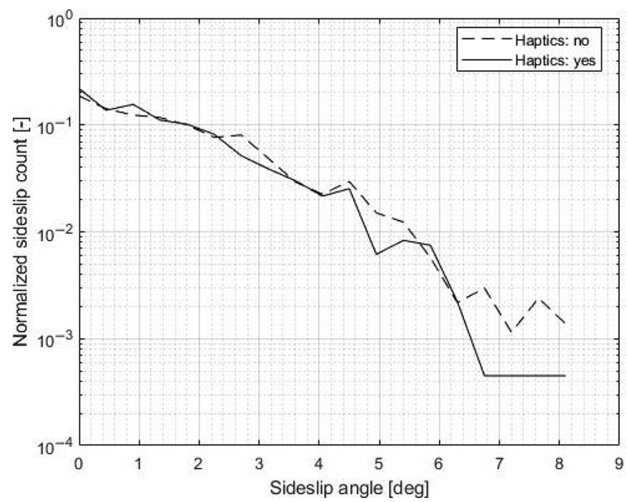
Results

The HF system was subjectively assessed in a horizontal straight flight at first. The range of AoA was 7°–19°. The angle was measured from an estimated horizontal aircraft axis. The speed range was from 80 to 180 km/h. The sliding element was described by the pilot and was sensible with changes in AoA but with continuous wobbling movement that was rather disturbing. The vibrations of rudder pedals activated when onboard side-slip indicator shows half of the ball out of the bracket at the cruise speed. The pilot commented that vibrations were well sensible and sidewise unambiguous. His perception of vibrations in flight was even better than on the flight simulator. Tilting movement of the sliding element during side-slip flight was assessed to be considerably worse than the one of vibrating pedals. This confirmed the fact that unsymmetrical HF on a control stick is better for roll guidance compared to yaw guidance.

Twelve horizontal turns were performed on the indicated airspeed of 140 km/h. Six right and six left turns were flown in a swopping order with and without haptic feedback. The mean side-slip angle was evaluated in the following manner. The angle of side-slip range was cut into short intervals. The counting of absolute value of side-slip angles duration for each interval gave its distribution. The distribution was normalized by dividing the total duration of the measured record for each turn, which means the areas under the curves in the Figure 3 are equal to one. This normalized distribution of side-slip angle was separately evaluated for each turn and for combined groups of turns with and without haptics (Figure 3).

The mean angle of side-slip was counted as a center of gravity of the area under the normalized sideslip distribution. The mean side-slip angles were compared by the one-tailed t-test. Mean values of side-slip angles in the turns without haptics is ($M = 1.86$ deg, $SD = 0.78$ deg) and in turns with haptics is ($M = 1.66$ deg, $SD = 0.43$ deg). This means that the difference is not statistically significant, i.e. $t(10) = 0.54$, $p = 0.30$. The count of normalized flight duration when aircraft sideslip was greater than the given threshold 5 deg was subsequently evaluated. The duration when the sideslip was greater than the threshold was ($M = 4.32$, $SD = 6.06$) per cent of the total time without haptics and ($M = 2.60$, $SD = 2.84$) per cent of total time with haptics. This means that haptics decreased side-slip angles above the threshold, but the difference is not statistically significant, i.e. $t(10) = 0.63$, $p = 0.27$.

Figure 3 Normalized sideslip angle distribution in turning flight



Discussion

The flight simulator tests pointed to strong inter-individual variations in the assessment of HF. The correlation matrix in Table II led to some unexpected results. While pilots were not instructed on how to work with turn coordinator during the experiment, they were asked about their approach afterwards. One pilot stated he was using solely the HF system in both flights where it was active. Another pilot was using solely HF in flight with AoS HF indication on the joystick. These pilots performed with the highest cumulative side-slip, but they both were flying the unfavourable variant of Latin squares, where HF flights preceded the flight with inactive HF. Other participants were using turn coordinator even in flight with HF active and they selected different ways to combine available readings. Some were regularly checking the turn coordinator; others were using it only to confirm their HF reading. Both groups agreed that HF increased their awareness of AoA and AoS but training with the system was insufficient for them to completely benefit from the HF usage.

The sliding element of the control stick was described by the pilot but with disturbing continuous wobbling movement during flight test. This movement of the control stick sliding element was attributed to the coarse digital conversion of the

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AoA input. Moreover, this fact influenced the accuracy of side-slip qualitative assessment.

During the flight simulator test, certain pilots doubted whether vibrations as HF are suitable for motorized aircraft. We were concerned that vibrations would interfere with the aircraft engine vibrations and that vibration of one pedal would spread to the other pedal devaluating the HF completely. Despite these concerns, the pilot perceived vibrations well sensible and sidewise unambiguous in the whole range of tested speeds. This is an improvement in flight test compared to the flight simulator test. The flight simulator rudder pedals use parallelogram guidance of the pedals with a short mechanical link between both pedals. The aircraft used for the flight tests was equipped with T-shaped rudder pedals with a longer and less stiff mechanical link between both pedals. This combined with a change in treadles shape and therefore change in pedals attachments housing the vibration motor led to the improvement of directional sensibility of rudder pedal vibrations.

The tilting function of the sliding element was confusing for a pilot. Therefore, the flight test was performed only with AoA signalizing by the sliding element. Note that the tilting movement of the control stick sliding element was concluded to be more suitable for a roll rather than yaw guidance. A pilot limb would be perceiving and acting in that case. Roll guidance by the tilting function of the control stick seems to be promising and should be analysed further.

Quantitative evaluation of the HF benefit was tested on the aircraft side-slip during 360 degrees turns. The overall side-slip decreased in case of flight with the HF, but the improvement was not statistically significant. This was attributed to a small statistical sample of twelve turns. The flight test was conducted by a single pilot. The flight simulator test indicated string inter-individual differences in the perception of HF. The test pilot did not complete training using the HF system. He/she only had experience from flight simulator tests of 2 h, for which he had participated five months before the flight test. Figure 3 shows normalized side-slip distribution in the course of twelve 360 degrees turns. There is a small decrease of sideslip with HF around the threshold of 5 degrees when the pedals vibrations were activated. It can be supposed that the decrease in the threshold value would help to decrease the sideslip during flight. The threshold level should be decreased only to an appropriate level. An extremely low value would lead to excessively frequent haptic information that would disturb a pilot during the flight without a positive effect. The second assumption for the HF benefit improvement is a pilot training on usage of the HF system. The system was designed to be intuitive, but ongoing research shows a significant learning effect for this pilot-aircraft interaction method.

There is another space for the HF system improvement. Vanes for both AoA and AoS were used in the flight test. These vanes are not suitable for common usage of the small aircraft because of their price and vulnerability during ground handling. The assumed solution for a commercially offered system of this type is expected to include AoA pitot tube that uses only pressure measurements for AoA sensing and lateral accelerometer to substitute the AoS measurements by the acceleration measurements. Such a hardware setup is recently used in avionics systems.

Conclusion

In this paper, we described the results of the evaluation of novel pilot-aircraft interaction method based on haptic interaction. Our results indicate that it is possible to substitute a part of the information typically perceived by the visual sense by haptic sense. The system capable of providing information about AoA and AoS comprises a sliding element embedded into the control stick and vibration elements mounted into rudder pedals. There are high inter-personal differences in the subjective assessment of the system. The results of the experiments indicate that the system can decrease the side-slip angles, even in critical phases of a flight. However, the difference was not evaluated as statistically significant mostly because of the relatively small sample size, high inter-personal variations and learning effect.

Further work

It is subject of the future work to improve the system to mitigate issues revealed during the evaluation. For instance, vibrations of the sliding element caused by quantization error will be resolved. Moreover, usage of the sliding element tilting for the indication of roll guidance should be investigated. Our future experiments should involve a longer training period to mitigate the learning effect and investigate the effects of the system on pilots that are properly trained to use it.

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Learning effect in joystick tactile guidance

Pavel Zikmund, Michaela Horpatzká and Miroslav Macík

***Abstract*—Haptic feedback is a method to provide tactile guidance in scenarios requiring multiple senses and divided attention like aviation. Earlier tests on a flight simulator and an in-flight test using the proposed tactile guidance method have shown the need to study its learning process. In this study, twelve participants completed two tactile guidance tasks without visual feedback across twelve sessions to analyze the learning effect. The paper shows an improvement between sessions in guidance accuracy, response time, and self-assessed workload. On the other hand, reaction delay is not affected by the training. The percentage improvement between the initial and trained skills reached 30 % in guidance accuracy performance.**

***Index Terms*—Human-Computer Interaction, Human Performance, Tactile Devices, Learning Effect.**

I. Introduction

Tactile guidance methods promise intuitive and easy operation. Despite the simplicity of use, many researchers show the presence of the learning effect, but only a few measure it. The learning effect is usually eliminated by prescribing different methods order for particular participants. That is possible in experiments comparing two or more guidance methods. Such experiments show the best guidance method among all tested methods. On the other hand, such experiments have a first impression character. The guidance methods performance of trained participants is not provided. The lack of participants' training increases results variance in the comparative experiments. One example is a recent study by de Rooij et al. [1], which presented a visual display to supplement haptic feedback on the side stick to maintain safe flight conditions. The experiment involved 15 professional pilots. The learning effect was observed, though it was not initially expected, as the pilots received training before the experiment.

The authors presented new hardware for tactile guidance [2]. The hardware consists of a joystick with a sliding element. The sliding element moves into or out of the handle surface of a joystick under the operator's fingers, see Fig. 1. The device has two main functions: warning and guidance. The vibration mode of the sliding element is dedicated to the warning. The front or back movement of the sliding element means guidance instruction. The primary motivation for the development of the device was the prevention of accidents caused by unwanted stalls and spins. Loss of control is the most common cause of general aviation accidents in recent decades. Consequently, authorities such as the NTSB [3] have repeatedly highlighted the loss of control in their most wanted list of transportation safety improvements. One of the possible methods for reducing the number of these accidents is by improving pilot-aircraft interaction. A loss of control occurs when the aircraft reaches a critical angle of attack and starts to stall. Stall warning systems are usually based on auditory and visual warnings in general aviation. However, Geehan [4] has presented findings that most pilots find haptic warnings to be more effective than auditory or visual alerts. Despite this fact, auditory and visual warning systems are more common due to their lower price. Although the presented device is applied to aviation, its use in other sectors using a joystick for any scenario involving guidance methods, such as control of work machines or telemanipulation is possible.

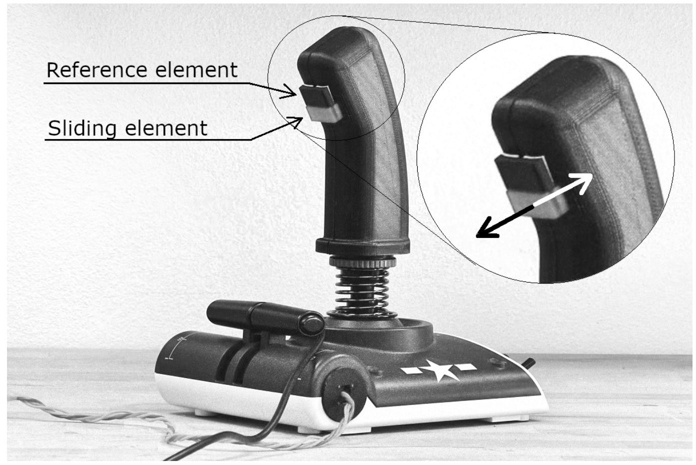

Fig. 1. Joystick with sliding and reference element used in the experiment. The reference element defines the position of the sliding element when the joystick is in the target position. The arrows represent possible sliding element movement directions.

In the previous research, the authors tested the system with tactile feedback on a flight simulator, and an in-flight test [5]. These tests did not show the expected improvement in pilot-aircraft interaction but revealed the necessity for defining a training process. Piloting relies on muscle memory, and the introduction of haptic feedback during rapid learning phases led to significant performance changes and an increase in measured parameter variances. Moreover, conducting training in flight tests would entail high costs when compared to laboratory investigations. Recognizing this, the primary focus of the research presented in this article is to explore and understand the learning curve associated with haptic feedback guidance. The learning effect is investigated on a guidance task without visual feedback. The reason is that pilots use mostly only peripheral vision for aircraft control feedback. Vision should stay reserved for other control and navigation tasks. The long-term goal of our haptic feedback research is to decrease the visual workload in aircraft control. The learning process in using haptic feedback is tracked over time through

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Manuscript submitted April 28, 2023; revised November 19, 2023 and February 6, 2024

This article has been accepted for publication in IEEE Transactions on Haptics. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TOH.2024.3368663

participants' performance. Understanding the learning curves will enable us to determine the necessary training required before conducting further tests, which should confirm or reject the benefit of haptic feedback in aircraft control.

II. Related work

The section summarizes the prior research and important aspects of haptic perception with a focus on tactile guidance on the learning effect. The interaction method described in this paper aims to be used in general aviation, where often one aircraft is used by several pilots with only moderate experience. Such a system requires fast learning, good memorability, adequate efficiency in its task, and minimizing user errors. These requirements are in accordance with the definition of classical usability by J. Nielsen [6]. Haptic perception involves both cutaneous and kinesthetic stimuli [7], [8], where most approaches to supplying various kinds of information to users rely on cutaneous stimuli. Systems involving haptic guidance are often used in application domains where the use of vision is limited or where vision is saturated by other tasks like aviation.

Aviation is a domain where haptic methods are frequently used, as the demands on vision are high, and divided attention could be the source of human errors. Haptic feedback has been a natural part of aircraft control since the beginning of heavier-than-air flight. The forces in aircraft main controls correspond to aerodynamic forces. The stiffness of controls increases with airspeed, and aerodynamic effects cause stick vibrations at low airspeed close to stall conditions when turbulent air hits the surface of the elevator. Modern aircraft with power steering simulate some natural effects by employing artificial systems. For instance, the stick shaker provides stall warnings [9] by vibrating the control column. More sophisticated systems aimed to provide even more detailed information about the angle-of-attack by modulating the vibrations [10]. The purpose this system is similar to ours, however our method is based on shape-change.

Several studies tried to employ haptic interaction as an additional channel to provide information in the aviation domain. For example, Van Erp [11] studied a tactile display consisting of 64 vibrotactile elements to help a pilot with guidance and control tasks. He found that the localized vibration on the pilot's body was easily coupled with spatial information, such as direction to a waypoint or threat. Cardin et al. [12] presented a system comprising eight vibrotactile actuators attached to the pilot's body. The system stimulates a pilot to catch his attention and provides information about the aircraft's attitude without needing to read the flight instruments. This research shows the benefits of haptic warning and guidance in comparison to only visual guidance during long-term flights. Fellah and Guiatni [13] proposed a tactile display to help with keeping an aircraft within safe limits and provide situational awareness support. The tactile display consisting of low-cost tactile actuators was designed to substitute the saturated visual channel. Vibration motors were placed on the pilot's body (abdomen, back, left, and right sides). The authors concluded that tactile feedback is suitable for feeding information about the aircraft's state. These sources highlight the opportunities and possibilities of using tactile feedback in aviation and illustrate how rich information can be provided through the haptic channel. On the contrary, they are inconvenient for general aviation as they require attaching tactile actuators directly to the pilot's body. Also, the mentioned studies do not focus on the influence of the participant's experience and details on how they learned to use the tested systems.

As described above, the application of the interaction method described in this study requires fast training and good memorability. The following paragraph focuses on these aspects in methods that involve haptic interaction. One of the frequently monitored parameters influencing performance during training is the time intervals between each training session. Wang et al. [14] investigated the training time interval duration influence on a tactile orientation discrimination task. Two compared groups trained at one-day and one-week intervals. The training intervals affected only the early stage of learning up to the third session. Both groups reached the same level after five sessions. Such results indicate that training intervals might be flexible if enough sessions are planned. Tactile perceptual learning has also been studied in the context of Braille script reading by Kass et al. [15]. They found that tactile learning is more intense between sessions than within a session. These findings correspond to previously published results by Karni and Sagi [16], [17] for visual learning. Other research papers are dedicated to auditory and visual perceptual learning. The concept of slow learning between sessions and fast learning within the first session were distinguished by Atienza et al. [18], Qu et al. [19], and Molloy et al. [20]. Ashley and Pearson [21] presented the importance of consolidation between sessions. Repeated within-day testing or overtraining leads to detrimental effects on perceptual learning. Consolidation of learned information during sleep has the power to prevent such deficits in learning. The time intervals between learning sessions have a minor or no effect on performance after a small number of sessions [14]. Performance improvement is more evident between learning sessions than within a session [15], except for the fast increase in performance within the first learning session [18]–[20]. These facts were reflected in the design of the experiment described in section III-B.

In order to evaluate the performance and improvement of pilots during tactile guidance training, various parameters might be used to measure the effectiveness of the training. These parameters include measures of accuracy, reaction time, workload, and situational awareness. In this paragraph, we focus on reaction times, while the measurement of guidance accuracy is discussed in the next paragraph. Reaction times in visual and tactile tasks were measured by Kim et al. [22]. The average tactile reaction time was 0.241 seconds, while the visual reaction time was 0.329 seconds. Workload and situational awareness were addressed by Elliot et al. [23]. They tested visual and tactile navigation displays in a navigation and guidance task in a strenuous outdoor environment. The research concluded that the visual display supported global awareness, while the tactile display supported local guidance, leading to a lower mental workload rating. The positive effect of tactile guidance on workload reduction was also reported by

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De Stigter, Mulder, and Van Paassen [24] in the study on application to a haptic flight director. An improvement in situational awareness was reported also in [13]. The aim of this study is to evaluate the effectiveness of tactile guidance methods, so we need to emphasize important measurable parameters along with results achieved by comparable methods. Humans can manifest faster reaction times to tactile stimuli than to visual ones [22], which further motivates the application of our method in the aviation domain. Tactile interaction might be better suited for local guidance, contributing to lower overall mental workload rating in combined tasks [23], [24], possibly leading to better situational awareness [13].

The effect of tactile feedback on the accuracy of guidance needs to be considered from several perspectives. Haptic guidance might improve the guidance accuracy as stated in [24] and by Nieuwenhuizen and Bulthoff [25] in the context of haptic shared control for personal aerial vehicles. On the other side, Voudouris et al. [26] state that the perception of tactile stimuli presented on a moving hand is systematically suppressed, which could be attributed to the limited capacity of the brain to process task-irrelevant sensory information. Authors investigated whether humans are able to enhance in parallel movement relevant tactile signals when performing goal-directed reaching movement. Conducted experiments suggest that participants were able to flexibly modulate tactile sensitivity by suppressing movement-irrelevant and enhancing movement-relevant signals in parallel when performing goal-reaching tasks. Juravle and Spence [27] investigated sensory suppression in complex motor tasks like juggling. The experiment required participants to detect gaps in the continuous signal provided by different modalities (haptic, auditory). The authors state that participants were significantly less sensitive to detecting a gap in tactile stimulation while juggling. The results demonstrate movement-related tactile sensory suppression related to the decision component in tactile suppression. Humans could trigger tactile suppression in the brain before the motor command. Tactile suppression might be a risk factor for the application of our method in aviation as humans may tend to suppress the tactile stimuli when focusing on another demanding task.

Other articles focus on the change in sensitivity to tactile stimuli. Chamnongthai et al. [28] propose a method to tackle the effect of temporal decrease of human force-detection capabilities in finger holder setups. They investigated the impact of Stochastic resonance on the user's haptic performance. The results show that human fingertip sensitivity significantly increases when Stochastic resonance is applied. Bensmaia et al. [29] investigate the effects of extended suprathreshold vibratory stimulation on the sensitivity of three types of neural afferents (slowly adapting Type 1, rapidly adapting, and Pacinian). The results show that prolonged suprathreshold stimulation can result in substantial desensitization of all neural afferent types. Temporal change in sensitivity to tactile stimuli – tactile adaptation should be reflected in the design and experiment as users will be in contact with the sliding element for long periods. Additionally, this factor is expected to have adverse effects on performance over time, potentially affecting within-session performance.

Interaction methods that employ tactile guidance have applications in many domains, including medicine, aviation, or even navigation of those with vision impairments. The frequent motivation factor is that the use of vision is limited in the particular domain, either by objective factors (visually impaired, low light environment) or by the overload of vision by another task (i.e., medicine, aviation). Many approaches related to tactile guidance rely on complex apparatuses directly connected to some part of the human body, e.g., [13]. Unlike that, we decided to follow the *come as you are* design constraint proposed by Triesch and Malsburg [30], which means that the users do not need to wear special equipment such as vests or gloves to use the system. This should enhance the acceptance of our method in the general aviation domain.

The analysis of the related work supports the need to investigate the learning effect of the proposed guidance method. Haptic feedback may help with faster skill acquisition and improve performance in path-following tasks. On the other hand, Sullivan, Pandey, Byrne, and O'Malley [31] observed a slight decrease in accuracy in setup with haptic feedback in research focused on movement smoothness while performing a mirror-tracking (path-following) task. Also, it is necessary to reflect on the effect of desensitization caused by physiological limitations of human neural afferents involved in the tactile sense as described by Bensmaia et al. [29] and by Chamnongthai et al. [28]. The experiment should focus on tactile guidance accuracy and reaction time and how these measures are affected by training. As suggested by Ashley and Pearson [21], the experiment should consider the effect of overtraining. In our experiment, we will measure performance changes within test sessions as well as between test sessions.

III. Method

A. Hardware

The hardware is based on the Mad Catz Pacific AV8R joystick, as shown in Fig 1. The shape of the joystick mechanism was modified to decrease the force peak needed to move out of the central position. The original handle was replaced by a handle with a sliding element. The sliding element performs a translational movement in and out of the joystick handle and is located under the operator's index finger. Just above the sliding element is the reference element. The reference element is rigid and represents the neutral position of the haptic guidance system. The operator's finger can be placed on the interface between these two elements, and information is obtained by comparing the position of the sliding element relative to the reference element. There are three main clues. If the sliding element is aligned with the reference (the operator can't feel any distinction between the elements), that means the target position is obtained and no action from the operator is required. In case the sliding element moves backward compared to a reference, that means the joystick should be pulled back. If the sliding element moves forward compared to a reference, the joystick should be moved forward as well (in this case, the operator feels a force of the sliding element moving towards his finger). If the required joystick movement is within one-quarter of the

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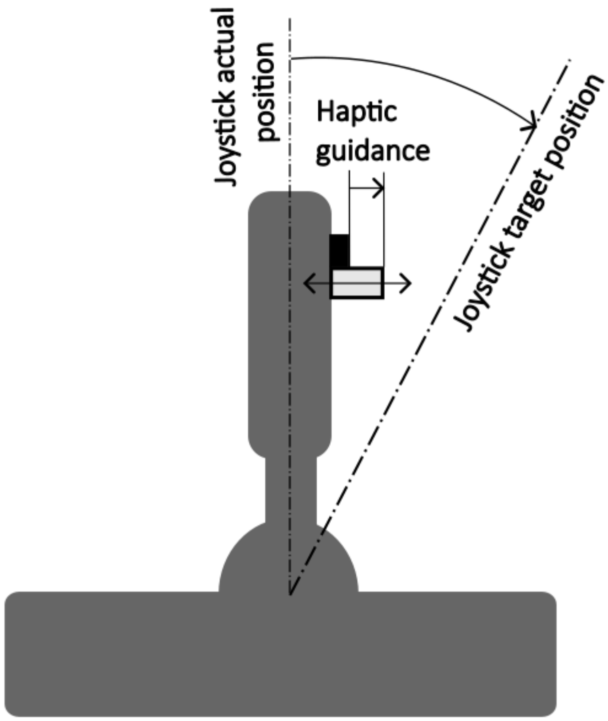

Fig. 2. The Haptic guidance dimension is proportional to the demanded trajectory of the joystick, ranging from the actual position to the target position. The Haptic guidance dimension reacts to continuous changes in both the actual and target positions.

joystick's range, the size of the position difference between the sliding element and the reference front surfaces is proportional to the joystick deflection required to reach the target position, as shown in Fig. 2. If higher deflection is required, the sliding element's deflection saturates at its maximum inner or outer position. The operator applies force only to the joystick handle. The sliding element then reacts to the actual position and indicates the distance to the target position. No force acting on the sliding element is required. The sliding element is powered by two SG90 digital servomotors, each providing a maximum force of 20 N, and its movement range is 8 mm. A vibration mode actuated by short-period front-back sliding element movements has not been used in this experiment.

B. Test procedure

Twelve undergraduate and graduate volunteer students were recruited to participate in this experiment. Participant eligibility was verified, and written informed consent was obtained from each participant. The group contained two females and ten males aged 19 to 26 (mean 21.67, SD 2.23). The participants were recruited from the student population in contrast to the previous simulator and flight tests where professional pilots were recruited [5]. The guidance task described in the following paragraphs did not involve aircraft dynamics. Therefore, no pilot skills were required to participate in this experiment. The subjects repeated the experiment in 12 sessions with a break between sessions of at least 8 hours. The mean time between sessions was 45 h (SD 36 h, and median 26 h) as shown in Fig. 3. The difference between the mean and median values is caused by weekend breaks between sessions. The maximum time between sessions was seven days due to an illness in the case of Participant no. 9.

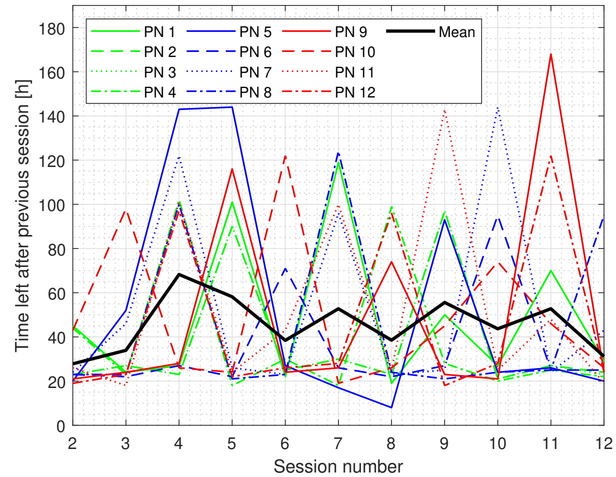

Fig. 3. The time between every two following sessions for all participants and the mean value.

Each session included two different tasks with no prior training. Both tasks have been done only once in the same order within each session. Subjects were guided only by the sliding element without any visual feedback. The computer screen provided information only about the beginning and end of each task but did not provide information during the experiments. As shown in Fig. 4, the first task was to guide the joystick to 20 randomly generated positions. Each position was generated as a constant random position with a uniform distribution over the joystick front-back travel range with a random duration uniformly distributed between 3 and 6 seconds. Both parameters were randomized across both sessions and participants. All participants used their dominant hand.

A continuously changing target position characterizes the second task shown in Fig. 5. Twelve different variants of 60-second courses of joystick movement were prerecorded before the experiment. The angular rotation speed of the joystick was (Mean 4.61 deg/s, SD 5.02 deg/s, and peak values of 30 deg/s). Each subject started with a different variant according to Latin square order. Each session contained one of the twelve variants. This helped eliminate the effect of the difficulty of variants from the learning effect. The subjects completed a short questionnaire after each session. They assessed their workload in both tasks. The Bedford workload rating scale published by Roscoe [32] was used. The questionnaire had a range from 1 to 10, where 1 means an insignificant workload and 10 means that is not possible to complete the task. Each subject received a USB stick as a reward after finishing all twelve testing sessions.

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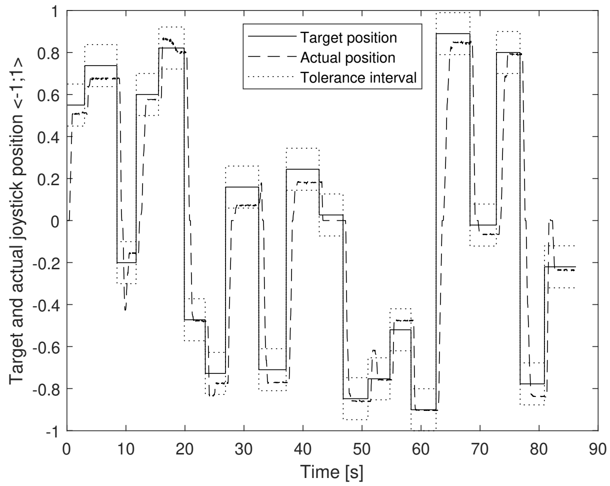

Fig. 4. One set of measured data from Task 1, illustrating the actual and target positions of the joystick over time. The task involves twenty random target positions.

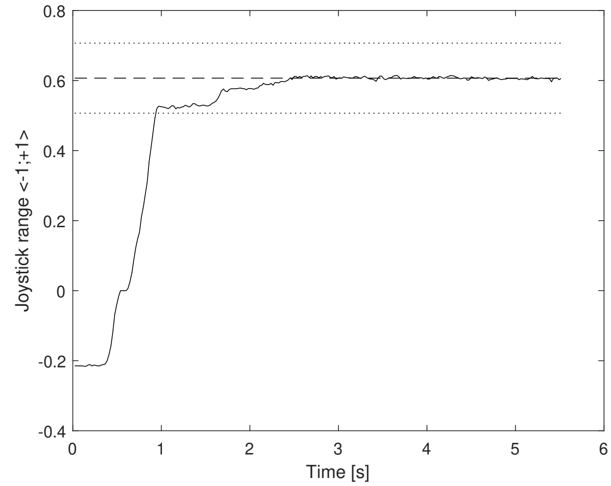

Fig. 6. This is one of the correct response records. The correct response was defined as reaching the target position tolerance interval without identified overshoot or non-minimum phase response.

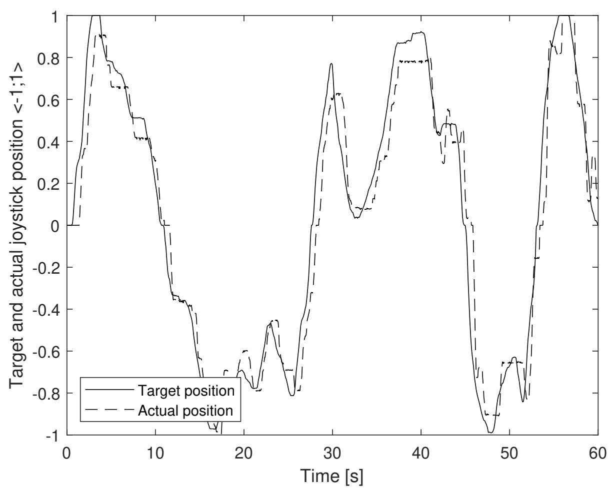

Fig. 5. One set of measured data from Task 2, illustrating the actual and target positions of the joystick over time.

C. Metrics

The learning effect was evaluated as an improvement of some quantitative criteria over time. The two main criteria were the time to reach the target position (TRTP) and the average error (AE). TRTP was measured from the time of the target position generation to the first reach of the target position tolerance interval. The tolerance interval was set at +-5 % of the joystick range around the target position. AE between the target and the actual joystick positions was measured from the first achievement of the target interval till the new target position was generated. These criteria were analyzed both between-session and within-session. Additional evaluated criteria were reaction delay (RD) and self-assessed workload. RD represents the time interval between the generation of the new target position and the beginning of the response. That means RD is a part of TRTP. TRTP and RD criteria were evaluated only for the first task. The second task was evaluated by the AE between the target and actual joystick positions.

The learning effect was assessed within-session for AE and TRTP in Task 1. For statistical analysis, twenty individual attempts were combined into ten levels. This was done by averaging each pair of consecutive attempts to create a new value for each level. This approach was necessary because Mauchly's test of Sphericity could not be applied when the number of repeated measurements exceeded the number of participants.

The mean values of all criteria were calculated for each session and each participant. The mean values of all parameters were analyzed by one-way repeated measures ANOVA to investigate the influence of the learning effect. In addition, Mauchly's test of sphericity indicates the assumption of sphericity and if Mauchly's test has been violated, Greenhouse-Geisser correction was used. The amount of $p < 0.05$ is considered as a significant difference. Finally, Post hoc analysis was done with Tukey's HSD Test. This test revealed homogeneous groups which helped to define the learning curve character along sessions.

D. Response characteristics

Most typical response characteristics were defined and identified among all the measured responses in Task 1. The correct response pattern is shown in Fig. 6. It was defined by reaching the target interval and remaining in it till the new random target position was generated. Two other conditions defining correct responses were that the overshoot and non-minimum phase response did not occur.

The overshoot refers to response characteristics crossing the target interval and returning back, remaining within the interval for the last second of the target position duration. The overshoot characteristic is shown in Fig. 7.

The non-minimum phase response is characterised by an incorrect initial decision regarding the response direction, as shown in Fig. 8.

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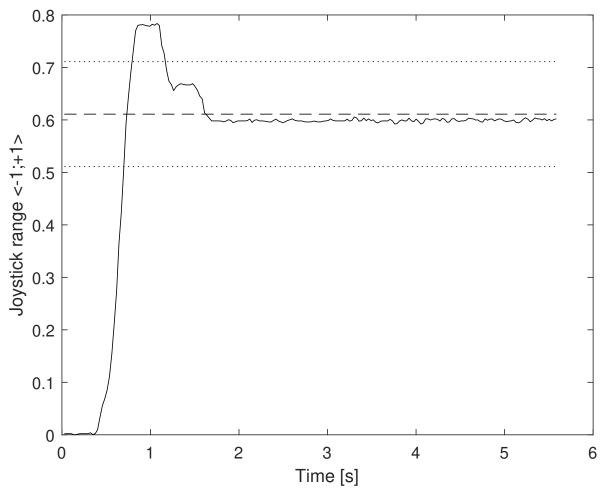

Fig. 7. A sample record of the response with overshoot. The overshoot was defined by crossing the tolerance interval and returning to it.

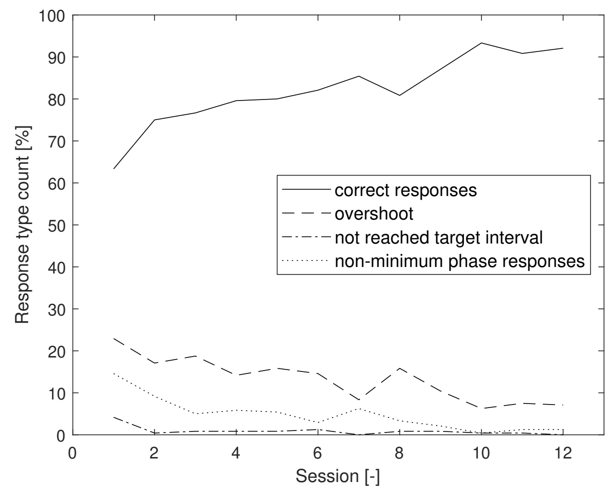

Fig. 9. The count of all participants' correct responses, responses with overshoot, responses without the reaching tolerance interval of the target position, and non-minimum phase responses over 12 sessions in Task 1.

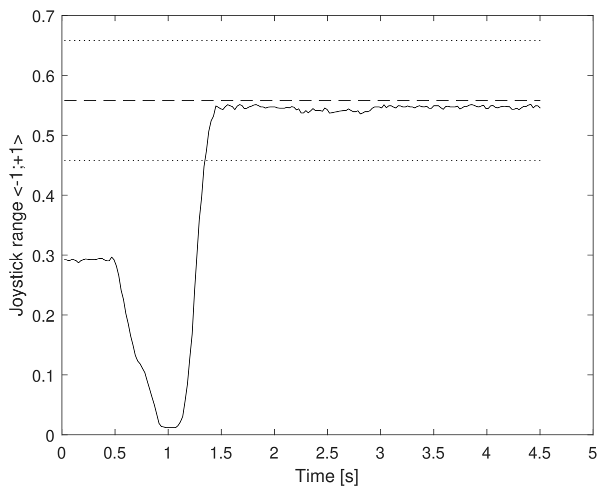

Fig. 8. A sample record of a non-minimum phase response. The non-minimum phase response includes all attempts where participants initially move in the opposite direction of the generated target position.

IV. Results

The chapter is divided into two parts corresponding to Task 1 and Task 2. The first part begins with the results of response characteristics, followed by a statistical evaluation for both tasks.

A. Task 1

1) Response characteristics: Twenty-six responses of all 2,880 attempts (0.9 %) did not reach the target interval till the last second of the interval duration. In this case, the time to reach the target position and the error between the target and actual positions were not defined in these attempts. The improvement of correct response attempts in Task 1 is shown in Fig. 9. The number improved from 63.3 % in the first session to over 90 % in the last three sessions. Other characteristic responses were overshoot and non-minimum phase responses. Three hundred and eighty-one attempts (13.22 %) include an overshoot of the target interval. The overshoot influenced the error between the actual and target positions in a negative way. The count of overshoot response improves from 22.9 % in the first session to 7.0 % in the last session. The time to reach a target position was not influenced or penalized by an overshoot. The non-minimum phase response includes a representation of one hundred and thirty-eight attempts (4.79 %). The non-minimum phase response negatively influenced the TRTP. The count of non-minimum responses improves from 14.58 % in the first session to equal or less than 1.25 % in the last three sessions.

2) Time to reach target position: TRTP Fig. 10 represents the mean values of each participant for each session. The TRTP showed statistical significance between sessions in repeated measures ANOVA with Greenhouse-Geisser correction (F (4.292, 47.21) = 2.782, p = 0.0341). Post hoc analysis was performed using Tukey's HSD Test, which revealed two homogeneous groups. These groups showed a significant improvement only in time between the first two sessions. The sessions from the second to the last can be grouped together as one homogeneous group, with a slight increase in TRTP value observed during the last two sessions.

The means of each participant's TRTP evaluated within-session are displayed in Fig. 11. The TRTP showed statistical significance within-session in repeated measures ANOVA with Greenhouse-Geisser correction (F (3.974, 43.719) = 5.161, p = 0.0017). Post hoc analysis revealed three homogeneous groups. The distribution of the homogeneous groups does not indicate any within-session learning effect of TRTP. Homogeneous groups revealed the best performance in the middle of Task 1 between attempts no. 9-14. The slowest response was achieved in an attempt no. 4-8 and 15-16.

3) Average error between target and actual joystick positions: The AE between the target and actual position of the joystick after the first achievement of the target interval Fig. 12 represents the mean values of the parameter for each

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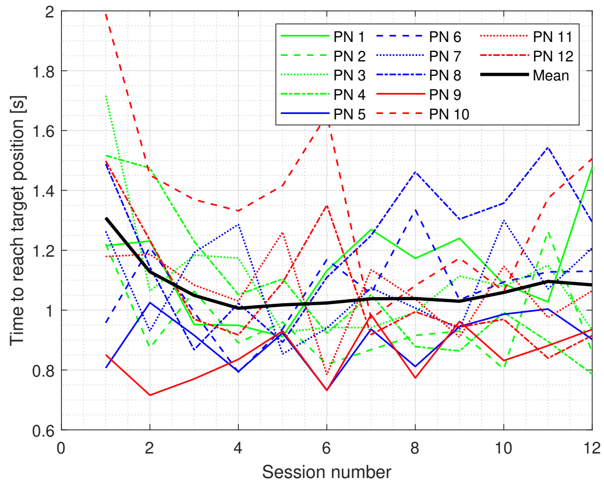

Fig. 10. Time to reach target position in Task 1 for all participants for each session. The time was measured from the generation of the new target position and the first reach of the tolerance interval.

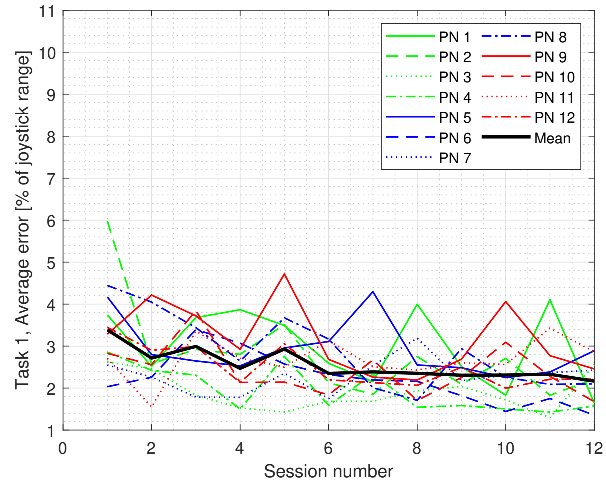

Fig. 12. Task 1: Improvement in guiding accuracy over 12 sessions. The accuracy is defined as the mean difference between the target and actual joystick positions after the first reach of the tolerance interval.

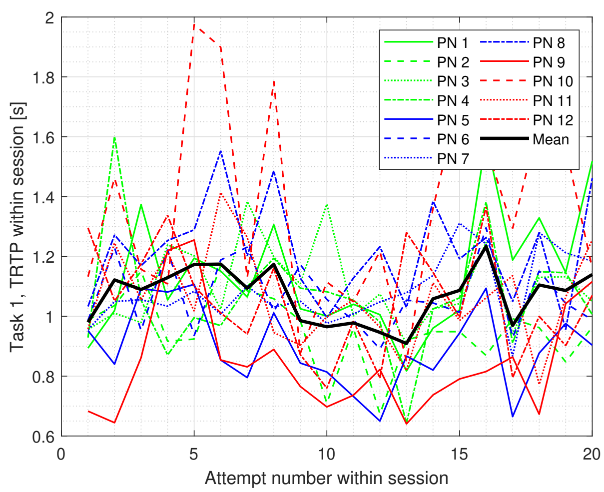

Fig. 11. Average time to reach target position in Task 1 for all participants within-session.

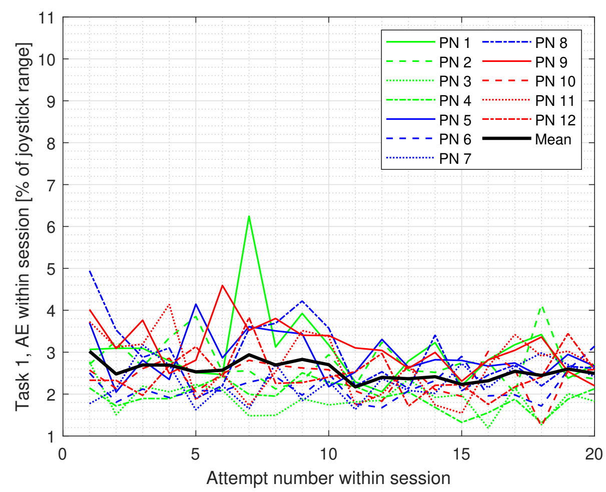

Fig. 13. Task 1: Average error between the target and actual joystick positions within-session over 20 attempts.

participant for each session. The AE showed statistical significance between sessions in repeated measures ANOVA with Greenhouse-Geisser correction (F (5.200, 57.206) = 4.256, p = 0.0021). Post hoc analysis revealed three homogeneous groups. Significant improvement is observed in the first six sessions, however sessions 3 and 5 indicate a reversal. An improvement cannot be distinguished from the sixth to the eleventh session. The mean value decreased from 3.39 % (SD = 1.08 %) in the first session to 2.16 % (SD = 0.51 %) in the last session.

AE was analyzed within-session, as well as TRTP. The means of each participant are shown Fig. 13. Again, twenty single attempts were merged into ten levels. The AE showed statistical significance in within-session repeated measures ANOVA (F (9, 99) = 2.462, p = 0.0141). Post hoc analysis was done with Tukey's HSD Test. However, despite the statistical significance in the ANOVA, post hoc revealed only a single homogeneous group consisting of all levels. The within-session learning effect on AE was not observed.

4) Reaction delay: RD represents the time interval between the generation of the new target position and the beginning of the response. Repeated measures ANOVA did not show any significant difference in RD along sessions (F (11, 121) = 1.265, p = 0.253). Mauchly's Sphericity Test was not violated in this case. The total mean value of RD is 0.4459 s (SD = 0.054 s). The fastest participant's mean reaction delay was only 0.369 s, whereas the slowest participant's mean reaction delay was 0.484 s.

5) Self-assessed workload: Workload assessments in both tasks were included in the questionnaire after each session. Participants ranked their workload using the Bedford workload scale. The maximum value on the scale used by the participant was 9 which means an extremely high workload with no spare capacity. This value was used only by Participant 1. He was

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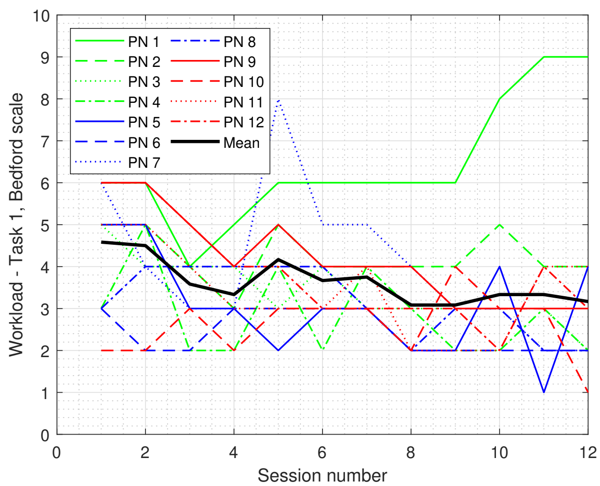

Fig. 14. Self-assessed workload in Task 1 over 12 sessions. Participant 1 was removed from ANOVA analysis as an outlier.

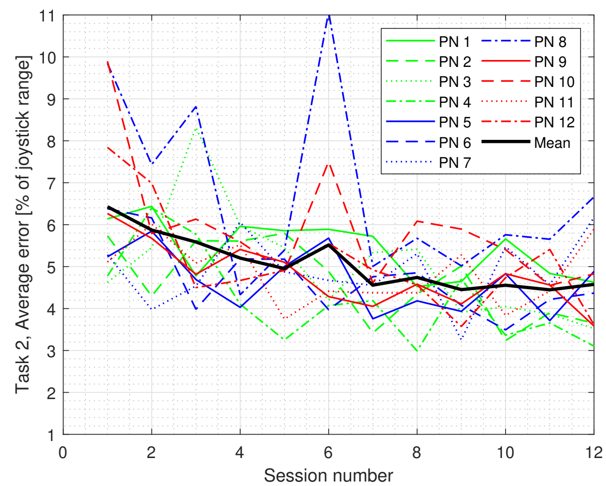

Fig. 15. Task 2: Average error between the target and actual joystick positions for each participant.

excluded from the evaluation as an outlier. He was the only one who assessed the workload as growing over the course of learning time as shown in Fig. 14. Possible reasons are stated in the discussion.

The last session was excluded from the ANOVA because of the same reason as merging attempts to levels in within-session analyses. The workload showed statistical significance between sessions in repeated measures ANOVA ($F(10, 100) = 5.176$, $p < 0.0001$). Post hoc analysis revealed three homogeneous groups. These groups displayed an improving trend until the eighth session. The mean values start around levels 4 and 5 on the Bedford scale. These levels are defined as "insufficient spare capacity for easy attention to additional tasks" and "reduced spare capacity, additional tasks cannot be given the desired amount of attention." The mean values at the end of the training were 2.81 (SD = 1.03). Values 2 and 3 are characterized as "Workload low" and "Enough spare capacity for all desirable additional tasks."

B. Task 2

1) Average error between target and actual joystick positions: The average error between the target and actual joystick positions throughout the second task in Fig. 15 represents the mean values for each participant. The AE in Task 2 showed statistical significance between sessions in repeated measures ANOVA with Greenhouse-Geisser correction ($F(4.0673, 44.741) = 5.222$, $p < 0.0001$). Post hoc analysis revealed three homogeneous groups. The homogeneous groups revealed no improvement after the seventh session. AE in Task 2 decreased from 6.43 % (SD = 1.83 %) in the first session to 4.58 % (SD = 1.16 %) in the last session. The reversal in the sixth session is given mostly by the coincident weak performance of Participants 8 and 10.

2) Self-assessed workload: The workload values on the Bedford's scale assessed for the second task differ slightly from the first task. No outliers were identified in the workload data for the second task. Each participant's means shows

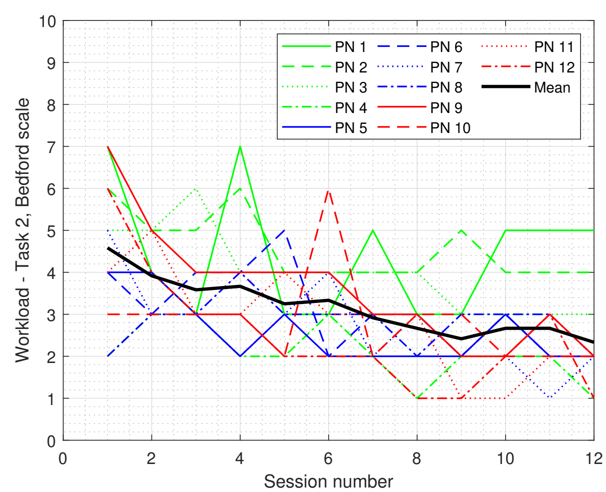

Fig. 16. Self-assessed workload in Task 2 over 12 sessions.

Fig. 16. The workload in Task 2 showed statistical significance between sessions in repeated measures ANOVA with Greenhouse-Geisser correction ($F(4.305, 47.355) = 7.082$, $p < 0.0001$). Post hoc analysis revealed five homogeneous groups. These groups demonstrate an improving trend throughout all twelve sessions except few reversals. The mean values start around levels 4 and 5 on the Bedford scale and reach 2.33 (SD = 1.15) at the end of the training.

V. Discussion

The measurement of the learning effect was the primary objective of the experiment. The specific research question was to assess the necessary training duration for the guidance method using the joystick with the sliding element. The effect is evaluated by considering the performance of the participants along with the session number. The average error (AE) and the time to reach the target position (TRTP) in Task 1 were evaluated both between-session and within-session.

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Building upon prior research by Zikmund et al. [2], which consisted of a single session, this study extended the investigation to 12 sessions. Two parameters that were measured in both experiments in the first session can be compared. The mean value of TRTP in the previous research was 1.548 s (SD = 0.48 s), while a recent result was 1.31 s (SD = 0.35 s). There was one difference in the Task 1 definition, which consisted of 30 attempts in the previous research. This difference might be due to the improvement of the guidance function of the sliding element during its development. Another parameter measured in the previous research was AE in Task 2, where the result was observed as 6.67 % (SD = 1.12 %), which is comparable to the value of 6.42 % (SD = 1.77 %) measured in the first session of the current study Task 2.

The parameter AE can also be compared between both tasks in the current study. Both tasks exhibit differences in their absolute values. One reason for this difference is that the AE measurement started after the first achievement of the target interval in the first task. AE in the second task was continuously measured throughout the entire guidance duration. The second reason is that guidance to a static position allows for a more precise reaction compared to continuously changing the target position in Task 2.

Within-session measurement of AE and TRTP parameters did not reveal a learning effect during the session. Within-session performance might be influenced by desensitization, as described by Bensmaia et al. [29]. Their results exhibit transitional characteristics that do not correspond to the within-session characteristics analysed in this study. A longer duration of Task 1 would be necessary to study this effect and distinguish between desensitization and within-session learning effects. Within-session results correspond to the findings by Kass et al. [15], who found more intense learning between-session in the case of tactile learning. Fast learning within the first session was not observed because within-session learning was analyzed for all sessions together.

Another aspect of tactile feedback applied to moving hand is suppressed or enhanced perception, as described by Voudouris et al. [26] and Juravle and Spence [27]. In our case, the movement of the hand and the sliding element are interconnected, forming a closed control loop. Thus, we hypothesize that, in this case, there is an enhancement of sensitivity as opposed to the suppression of sensitivity during task-irrelevant movement.

Reaction delay (RD) is not significantly affected by the training. We can decompose RD into perception and decision time. The perception of tactile input was estimated at 0.241 s by a method suggested by Kim et al. [22]. Thus, we can expect that the difference of approximately 0.2 s corresponds to decision time. At this point, the participant decides the direction of the reaction. The success rate in the decision is shown in Fig. 9. Even though the decision time did not change, the rate of correct decisions, described by the non-minimum phase response count, increased significantly.

The next parameter for defining the learning effect was workload. Participant number 1 was excluded as an outlier in the case of workload in Task 1. The Participant's performance did not stand out of the general trend, but his self-assessed workload in Task 1 did. The Participant considers this self-assessment as a sign of perfectionism. This raises the question: why does his self-assessed workload in Task 2 indicate only a slight increase in the last three sessions? A possible answer could be found in two aspects. The first is the magnitude of sliding element deflections from the reference element. The first task appears to be easier in guiding participants to static positions. After reaching the position, participants stopped moving and waited for a new target position to be generated. However, haptic guidance sometimes started with full sliding element deflection, which meant high joystick deflection was required. In contrast, the second task required continuous effort, but the sliding element deflections were possible to keep low throughout Task 2. The second aspect is the order of the tasks. Task 1 was always the first, followed by Task 2. Participants started Task 2 after refreshing their skills in Task 1. We assume that this fact explains why the workload was assessed as lower for Task 2, while the AE was measured as lower in Task 1 due to the different difficulty levels of both tasks.

To answer the principal research question of necessary training duration, one needs to focus on courses of TRTP and RD over repeated sessions. While the TRTP and RD did not show significant learning effect, AE is the most important parameter to consider in training duration. Significant improvement was also observed in the self-assessed workload. However, it cannot be measured as exactly as the AE while its assessment is subjective. Considering AE, the learning effect breaks in the 6th session in Task 1 and the 7th session in Task 2. Participants' improvement after these sessions indicates only insignificant progress. This study did not evaluate the effect of interval duration between sessions.

The training interval duration between sessions affects the learning effect in the early stage, according to Wang et al. [14]. The seven sessions required to reach the trained skills from our results are much greater than the three sessions in Wang's study, where the time between sessions affected training performance. Additionally, the peak values in the intervals between sessions shown in Fig. 3 do not correspond to any peaks in TRTP, AE, or workload performance across sessions. The stated interval duration between training sessions should provide sufficient time for consolidation to prevent overtraining. Except in one case, all intervals between sessions included at least one night. However, due to the limited number of sessions and participants, a more detailed analysis of the effects of the intervals between sessions was not possible.

There is one effect that should not be neglected in the learning effect evaluation. Figures 10 – 15 demonstrate individual differences between participants. That led us to an individual training proposal. Individual training should be defined based on the improvement and achievement of the required performance in both tasks. The required performance might be set as values where the observed parameters converged in this experiment. We propose the following target values to complete the training based on the results presented in Tab. I. The proposed values apply only to the used hardware and participants with an average performance. Therefore, the following criterion for stating that the learning process is completed could be evaluated as a percentage of performance

TABLE I
TARGET PARAMETER VALUES AFTER TRAINING

	Task 1	Task 2
AE [% of joystick range]		
	2.4	4.7
Workload [Bedford scale]		
	3	3

TABLE II
PERCENTAGE IMPROVEMENT WITH RESPECT TO FIRST SESSION PERFORMANCE

Session	AE 1 [%]	AE 2 [%]
1	0	0
6	-30.7	-14.2
7	-29.6	-29.1
12	-36.1	-28.8

improvement. Tab. II shows the relative mean improvement in AE for the sixth, seventh and twelfth sessions compared to performance in the first session. We propose a value of 30 % for relative improvement to indicate that training is completed. The value of 30 % for relative improvement corresponds to other research in tactile learning, as previously mentioned by Kass et al. [15] and Wang et al. [14].

Some other limitations of the work might be found in the following aspects. Our experiment involved only the dominant hand, and participants largely used the same joystick handle grasping technique. We assume that different grasping techniques could affect the performance of haptic guidance. However, this effect could potentially be stronger if vibrations were used, as suggested by Harris et al. [33]. Their study pointed to the fact that human tactile learning is topographically distributed. Trained skills in vibration discrimination did not transfer to other fingers; however, skills in pressure and roughness discrimination are transferred to other fingers. The short duration of each session limited our ability to fully analyze the within-session learning effect, as well as the effect of neural afferents. The application of our results to longer-duration guidance tasks may be influenced by this limitation. Therefore, we propose conducting another experiment after the training phase to analyze the effect of haptic perception over time, which would be separated from the learning curve effect. Tactile suppression may also impact participants' performance when focusing on other demanding tasks. Therefore, haptic guidance should be tested in parallel task scenarios and during high-workload pilot situations.

The definition of the learning effect for the tactile guidance method allows for planning a new set of experiments for investigating the effect on flight performance/safety. Future aerospace engineering research should explore crossover research that compares the efficacy of visual and tactile guidance and their interactions. While visual guidance is more effective than tactile guidance in simple tasks, a comparative study of these methods is needed for situations where the visual modality is overloaded, such as in aircraft control during an emergency situation. The next research step involves the implementation of aircraft dynamics. At this stage, haptic guidance should be tested with trained professional pilots to confirm the potential benefits in aircraft control. Moreover, the proposed tactile guidance method could have applications in contexts that require divided attention and the simultaneous use of multiple senses. For example, this method could be used for remote operation of machinery and medical devices, navigation of people with vision impairments, and in the automotive industry.

VI. CONCLUSION

We have presented experimental results that led to the definition of the learning effect for the tactile guidance task. Human participants tested the proposed tactile guidance method in a set of position-targeting and trajectory-following tasks. The participant's performance progress between sessions shows an improving trend, particularly in the first seven sessions. The average error between the actual and target positions and the self-assessed workload are parameters significantly influenced by the training. On the other hand, reaction delay was not significantly influenced by training and time to reach the target position improvement was identified only between the first two sessions.

Achievable performance in tactile guidance has been presented. The guidance accuracy expressed in the average error between the target and actual position is less than 5 % of the joystick range in the trajectory-following tack. This value means a competitive result in comparison to other tactile guidance methods [34], [35]. These results are valid only for the proposed haptic feedback device. However, the presentation of hardware setup and corresponding performance might be useful for designing novel tactile guidance methods. The performance in haptic guidance is individual. In order to apply the results to define an individual training setup, we propose the additional criterion for defining trained skills as an improvement of 30 % over consecutive sessions in the average error between the target and actual positions between the initial and trained skills.

ACKNOWLEDGMENTS

This research has been supported by TACR, project no. TJ01000122 "Haptic feedback of assistant systems for flight safety improvement", by project No. FSI-S-23-8163 funded by The Ministry of Education, Youth and Sport (MEYS, MŠMT in Czech) institutional support and partially by the Research Center for Informatics project CZ.02.1.01/0.0/0.0/16 019/0000765. The authors thank Assoc. Prof. Zdeněk Karpíšek of the Institute of mathematics at Brno University of Technology for his support in the analysis of results and to anonymous reviewers for their conductive comments.

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Journal of Physics: Conference Series

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More Haptic Aircraft

To cite this article: P Zikmund *et al* 2024 *J. Phys.: Conf. Ser.* **2716** 012074

More Haptic Aircraft

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Abstract. This paper presents a comprehensive review of haptic feedback in light aircraft control. It provides an overview of the results and experiences gained from a previous research project focused on the design and testing of pilot haptic feedback hardware. The objective of this paper is to outline a roadmap for the future development of "More Haptic Aircraft," incorporating principles of human-centred design into light aircraft cockpits equipped with the presented haptic feedback device. The roadmap provides general requirements for pilot-aircraft interaction and highlights three specific levels of functions. These functions aim to reduce the pilot's workload and enhance situational awareness.

1. Introduction

In modern aircraft control, the visual modality has become saturated [1]. While this is not problematic under standard conditions, it can lead to a reduction in situational awareness during unexpected or emergency events. Another challenge, particularly in general aviation aircraft, is that the aircraft control still employs speed, rather than angle of attack (AoA), as its primary parameter. Both speed and AoA are conveyed through the visual modality. In contrast, flying animals gauge speed and angle of attack through tactile or haptic perceptions. For instance, birds detect speed based on the vibrations of their feathers, while insects do so through the vibrations of their hairs. This suggests potential ways to enhance pilot-aircraft interactions and improve pilots' situational awareness through haptic feedback, offering an artificial sensation of airflow parameters such as AoA and Angle of Sideslip (AoS). In this paper, the authors aim to explore the role of haptics in aircraft control, taking into account recent advancements in both the haptics and light aircraft control domains. The basic principles of human-centred design are also considered to lay out a roadmap for the new cockpit of light aircraft.

1.1. Background

Over the past century, primary aircraft control mechanisms, such as ailerons for roll, elevators for pitch, and rudders for yaw, have remained consistent. However, aircraft systems and cockpits have seen noteworthy progress. This change is illustrated in **Figure 1**. All these systems were designed with the goal of increasing flight safety. Concurrently, these advancements have heightened the demands on a pilot's instrumental situational awareness, one of three levels of situational awareness as defined Endsley [2]. One of the major changes in recent decades has been the implementation of the glass cockpit. The glass cockpit has increased the amount of information a pilot can access and must process. It can be anticipated that aircraft control will evolve in tandem with rapid advancements in human-machine interaction observed in other disciplines such as car driving, human-computer interaction, or even military aircraft control.

Figure 1 Comparison of two aircraft cockpits a century apart. Left side is SPAD XIII from1918, the right side is Cessna 182 Skylane from 2010 [3]

1.2. Artificial haptic feedback in aircraft control

Recent research has highlighted a promising approach for pilot-aircraft interaction: the incorporation of artificial haptic feedback into aircraft controls. The authors designed and tested active pedals and a stick in response to the high demands on visual modality. The hardware, as shown in **Figure 2**, was designed to convey AoA and AoS to a pilot through haptic feedback [4]. The test confirmed the readability of the haptic cues, including the vibrations in the pedals and the sliding element in the control stick in flight conditions. The sliding element, located on the left side of the figure, moves in the indicated direction inside or outside of the stick handle. A pilot can feel its position with his/her fingers. The most precise information is provided around the zero position, where the sliding element is close to a fixed reference element placed just above the sliding element. The pilot can feel the edge between the elements or just a smooth transition at the zero position of the sliding element. The pedals on the right side of the picture provide haptic feedback through vibrations. The greater the AoS, the higher the frequency of vibration intervals appears. In this paper, the potential usage and application in pilot-aircraft interaction are elaborated and discussed.

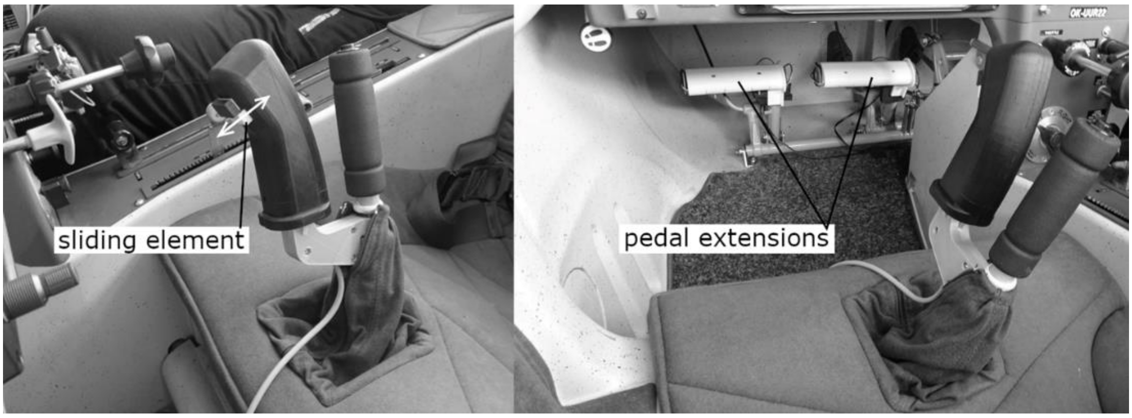

Figure 2 Hardware conveying AoA and AoS to a pilot through haptic feedback [4]

1.3. Human-centred design principles

A comprehensive introduction to human-centred design presented Billings [5]. His key points are summarized in this paragraph which lay out principles and guidelines focused on human-centred automation in aircraft and the broader aviation system. A motivation for this work comes from aircraft accidents linked to the “Loss of Situational Awareness”. This loss can be attributed to multiple factors including complexity, coupling, autonomy, and inadequate feedback. **Complexity**: Increasing complexity of automation systems makes the aircraft control more difficult for the pilot. **Coupling**: This refers to the often-obscured interactions between automation systems. **Autonomy**: This entails self-initiated automated system actions, placing the pilot in occasionally challenging situations where they must decide if the observed behaviour is appropriate or not. **Inadequate feedback**: This situation arises when humans are left uninformed about the actions and decisions of the automation system. Given these challenges, the principles of human-centred design are posited as:

- The pilot must be actively Involved and adequately Informed.
- The pilot must be able to monitor the assisting automation.
- The automated systems must be predictable.
- The automated systems must also monitor the pilot.
- Every Intelligent system element must understand the Intent of other Intelligent system elements.

In addition to the principles of human-centred design, there is a demand for methods to assess pilot-aircraft interaction. One of the most widely used methods for cognitive modelling is the Model Human Processor (MHP), developed by Card et al. [6]. The MHP is designed to calculate the duration required to complete specific tasks. This model, which incorporates factors such as processor cycle times and memory decay durations, assists system designers to predict time efficiency of human operator interacting with the analysed system.

1.4. Research Objective
Given the topics discussed in the introduction section, following research questions have been posed. The answers to these questions should help identify possible ways to enhance cockpits and pilot-aircraft interaction in the segment of light aircraft.

- How can human-centred design principles be utilized to improve safety and efficiency in light aircraft control?
- How can pilot-aircraft interaction be optimized to reduce workload and enhance situational awareness?
- What types of information could be conveyed by haptic feedback to improve pilot-aircraft interaction?

2. Human centred design and haptics in light aircraft control: A review
The application of human-centred design principles is not new in the aircraft domain. This design evolved alongside the parallel implementation of automated systems in both large and military aircraft. Boy and Tessier [7] introduced a method called MESSAGE for cockpit analysis and assessment. This method utilizes a multi-task/multi-channel model to measure both workload and pilot performance. Over the last decade, another common research topic has been the single-pilot cockpit for airline operations. Graham et al. [8] presents a study that compares a two-pilot cockpit with a single pilot cockpit equipped with an onboard support system that automates some of the functions typically performed by a co-pilot. This study evaluates life-cycle cost, reliability, and processing times for flight procedures based on MHP. The topic of the single-pilot cockpit introduces the concept of fault-tolerant cockpit architecture, discussed in detail by Fayollas et al [9]. A comprehensive study by Boy [10] profits the author’s extensive experience in human-centred design. This paper introduces three conceptual models, providing a framework to understand and address operationalization issues in complex systems. The author highlights a shift from hardware to software in the design and development process, termed the “socio-technical inversion”. While the mentioned publications represent only a fraction of the extensive research on the human-centred design of aircraft cockpits, they left limited room for improvement using

general principles of human-centred design. Conversely, the domain of light aircraft remains less impacted by automation and is similarly less researched in terms of human-centred design.

2.1. Light aircraft cockpit
In the last few years, there has been a trend of replacing analogue instruments with digital ones, the so-called Glass cockpit. This study [11] dealt with the topic of implementing glass cockpits in light aircraft from the safety point of view. At the same time, it proved that the introduction of glass cockpits did not lead to the expected increase in safety compared to similar aircraft with traditional equipment. Advanced avionics have the potential to increase this safety by providing pilots with more operational information, but more effort is needed for pilots to take advantage of this potential. Currently, touch screens are also coming to the fore. In this respect, especially for light aircraft, it is also necessary to address overall ergonomics, human factors, and operational practicality, and thus not only replace the original display with the touch screen [12]. Glass cockpits have the potential to enable a change in the distribution of information during individual flight phases. This issue was addressed in this paper [13], which investigated what information is most important for given phases of flight, where it should be located, how large it should be, and when and why it should be displayed. The analysis of eye movement on individual devices was dealt with in this work [14]. Pilots participating in the experiment were to perform a standard circuit under visual flight rules. The study assigns to each phase of flight the attention the pilot pays to each instrument.

2.2. Previous Research Projects in Haptic feedback
In [1], a roadmap for the development of artificial airflow sensation via haptic feedback was introduced. This roadmap led to the formulation of a unique guidance method utilizing haptic feedback as described in [15]. The efficacy of the haptic guidance method was notable, with root mean square error of just a few percentages of the front-back joystick range between the target and the actual joystick position. While the hardware was applied in flight test mediating AoA via haptic way, it has not yet been integrated into any pilot assistance systems, such as landing aids or stall warning systems. Concurrently, other research teams have turned their attention to the potential applications of haptic technology in the realm of aircraft control. D’Intino et al. [16] delved into the potential of a haptic support system in mastering a 2 degrees of freedom compensatory tracking task. This haptic assistance incorporated force feedback. To assess the efficacy of the haptic support system, a human-in-the-loop experiment was conducted with novices using a fixed-base simulator. The haptic aid proved advantageous during the tracking task’s training phase for both axes when compared with manual control. These findings have paved the way for further exploration into the creation of sophisticated haptic support systems capable of adjusting to a user’s proficiency, thus offering tailored feedback.

Deldycke et al. [17] introduced a tool designed to aid in manual flare manoeuvre training. The study indicated only a marginal enhancement during the training’s onset. Nevertheless, the haptic feedback led to a more uniform beginning of the flare. The researchers concluded that while the haptic aid offers potential in manual flare manoeuvre training, there is a need for additional research to augment its efficiency. It is crucial to acknowledge that the perception and response to haptic feedback are highly individualized. A paper by Arenella et al. [18] underscored this by emphasizing the tailoring of the Haptic system to individual pilots. They embarked on crafting an Adaptive Haptic Aid system that modulates the assistance level on the control apparatus based on the pilot’s real-time performance relative to the anticipated outcome. Both simulations and hands-on trials with novice and veteran pilots demonstrated that the proposed Adaptive Haptic Aid system holds significant potential for the future design of haptic aids. Recent research undertakings are also geared towards enhancing haptic feedback in fly-by-wire controls. For instance, Van Baelen et al. [19] presented flight envelope protection through haptic feedback, incorporating both force and vibrations in the control stick. This system assists pilots in evading flight envelope speed and load factor threshold values, especially when there is a shift to an alternative control law.

2.2.1. Results and experiences: While the hardware was designed to be user-friendly, flight testing revealed the appearance of a learning effect. To demonstrate this training effect in haptic guidance, twelve undergraduate and graduate volunteer students aged 19 to 26 (mean 21.67, SD 2.23) were recruited to participate in the experiment. The test comprised two tasks, each repeated twelve times by each participant. The first task involved guiding the joystick to 20 randomly generated front-back directional positions with random duration from 3 to 6 seconds, while the second task, as illustrated in **Figure 3**, required guidance to a continuously changing target position. Both tasks were performed without any visual feedback, and the entire test took approximately 3 minutes to complete. The results indicated that starting from the seventh session, participants were able to track the continuously changing target position of the joystick with an error rate of less than 5 percent of the joystick's range. The error rate in the first task, which involved guidance to randomly generated positions, was even lower. A more detailed experiment description with statistical evaluation will be published soon.

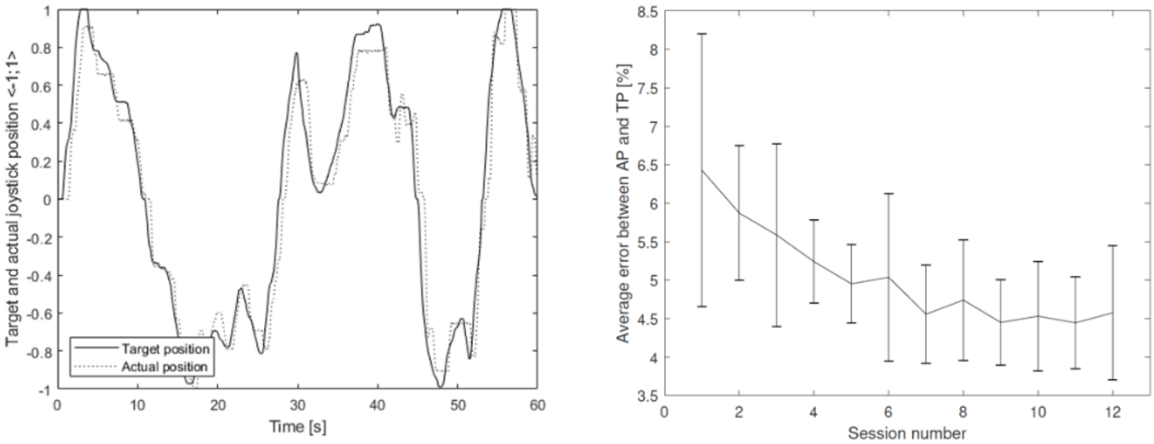

Figure 3 Results obtained in a haptic guidance task without visual assistance. On the left side, a sample task displays the target and actual joystick positions. On the right side, the graph illustrates the mean error between target and actual positions for all participants along sessions.

3. Roadmap for Future Development: "More Haptic Aircraft"

Sensory overload (especially in the case of vision) can be successfully addressed by representing information to maintain good situational awareness using other sensory modalities. Auditory modality is routinely used even in light aircraft to complement visual instruments (e.g., for stall warnings or audio variometers in gliders). Haptic feedback is also a part of light airplane control naturally - the stiffness of control changes appropriately to airspeed, or the vibrations to the control stick appear if the plane approaches stall speed. In complex planes with power-assisted controls, this natural interaction is still simulated with systems like stick-shaker.

Systems based on haptic interaction (providing artificial tactile and/or kinaesthetic stimuli) can successfully supplement vision as a primary sensory modality in aviation. The systems can potentially be used for the following tasks:

- **Notifications:** Haptic systems notifies to attract his/her attention to something. The situation is later evaluated also by other means/sources of information. Examples are simple stick-shaker or auditory stall warning.
- **Feedback:** Haptic system provides any system response using touch cues. Vibrations, force or any other touch sensation can by exploit to give the response to a user.
- **Guidance:** Haptic system provides guidance towards particular position in X-dimensional space. It can be position of a control or position relative to aircraft frame of reference (e.g.

waypoint position). Example of such a system is flight-director, that already has its haptic variant published by De Stigter [20].
- **Expressing complex information.** Haptic systems can convey even complex spatial-temporal information. Typically, various kinds or tactile displays are used [21]. However, the practical application of complex systems relying on actuators mounted pilot skin is questionable for light aircraft cockpit.

The following aspects define classical usability [22] and should be considered for designing future human-centred systems for light aircraft.

- **Learnability:** The designed system should require only a little training. In the best case, a particular design can achieve affordance (self-explanability) from the user's perspective. The pilot should rapidly achieve proficiency in the usage of the system.
- **Efficiency:** The design is efficient in its primary task of conveying specific information to maintain situational awareness.
- **Retention over time:** when a pilot returns to using the system after an extended period of time, it should be easy for the pilot to regain the associated proficiency quickly.
- **Low error rate:** The system design will cause as few errors (e.g., value misinterpretation) as possible. It will provide cues to allow pilots to detect possible errors. The new system mustn't interfere with existing ones.
- **Subjectively pleasing:** The acceptance of a new system design also relies on subjective assessment of users - pilots. Properties like shape or materials should be carefully considered.

Apart from classical usability and consideration of human-centred design in aviation described in [5], the following aspects of a haptic system for light aircraft should be considered:

- **Portability** of a new system and possibility of **retrofitting** into existing aircraft. In case of light aircraft, new systems should allow retrofitting into existing aircraft and integration with existing systems. Systems that are carried-in by the pilot can make the integration more complicated, on the contrary, they will allow better adaptivity. Potentially, individuals can accept more intrusive systems (e.g., devices relying on skin contact) if they are in their possession.
- **Adaptivity** of data presentation. The amount, coding and scales of the represented information can be adapted e.g., accordingly to flight phase/aircraft configuration or personalized on basis of individual's requirements and preferences. However, the future system should preserve transparency of its function to avoid errors.

3.1. Haptic feedback applications to light aircraft control
The introduced hardware may have multiple functions in aircraft control. These functions can be divided into three levels. **The first level** serves a warning function (provides notification and feedback). Front-to-back vibrating movements of the sliding element can alert a pilot about approaching stall conditions. This function can supply the shaker warning system typical for large aircraft. Similarly, **the second level** can be likened to the function of a pusher system (provides feedback and guidance). If the pilot does not respond to warning vibrations, the sliding element can signal a command to push the stick with an accentuated movement in the front direction. The system does not actually push the stick but gives a clear haptic command indicating the necessary control action. **The third level** is comparable to a complex flight director system (provides feedback and guidance). The moving element retains the same guidance function as in the second level. However, this third level requires a system that knows or can estimate the target or optimal flight trajectory.

A similar application was published by De Stigter et al. [20], where a haptic director aided pilots in enhancing their performance in a trajectory-following task. The distinction with the hardware they used is that it controlled stick forces in the sidestick, moving the zero-force position in roll and pitch control, which subsequently led to task performance improvement. This third level necessitates an intelligent control system that offers guidance assistance to the pilot, for instance, during a flare manoeuvre. Another potential application might be supplying of haptic feedback in a fly-by-wire control system.

3.2. Discussion

Let's confront the proposed applications from the previous section with the research questions. Especially the first two levels supplying the function of the stick shaker and pusher were suggested aiming to improve the safety of flying in light aircraft. The real shaker and pusher used in large aircraft are not suitable for light aircraft due to the weight and costs of the systems. The efficiency of the aircraft could be linked to a possible extension of haptics to the third level. The haptic flight director could assist the pilot in flying more efficiently or even accelerate pilot training.

The second question concerns the reduction of workload and enhancement of situational awareness. This point might be found in the transfer of some information from the visual modality to a haptic one. The optimization of information flow in the cockpit could be analysed and optimized using MHP. The improvement of the pilot-aircraft interaction should have a positive impact on both the pilot's workload and situational awareness.

The last question aims to identify particular information that could improve pilot-aircraft interaction. In the first level stated in section 3.1, the information is connected to the AoA. It can be information proportional to the AoA value or its margin to the critical value. In higher levels, the information can be more complex. In this case, research must be conducted on the personalization of haptic feedback perception. Learnability, retention over time, and adaptivity should be measured and analysed to exploit the maximum benefit from the haptic system.

4. Conclusions

Human-machine interaction has been identified as an ongoing topic in general aviation. Recent avionics advancements in light aircraft provide pilots with richer and more detailed data than in the past. However, this also increases the demands on workload and situational awareness for the pilot. A general goal of this paper is to address the challenge of maintaining pilot situational awareness during the use of automation or under challenging or emergency conditions.

The authors have combined their expertise and results from haptic feedback systems with the general principles of human-centred design to devise a roadmap for the future design of light aircraft cockpits. The haptic feedback system, when connected to a control stick and pedals, can convey information about flow field characteristics to the pilot through tactile feedback. The presented roadmap offers both general guidelines and potential applications, drawing inspiration from large commercial aircraft systems.

The outcome of the paper highlights the necessity of integrating human-centred design principles into the design of future light aircraft cockpits. Increasing avionics complexity should be reflected in multimodal optimization of pilot-aircraft interaction. Several warning, feedback, and guidance cues could be transferred from the visual to tactile modality. However, this shift also introduces new challenges in the subjective perception of tactile cues, which should be a subject of future research.

Acknowledgments

This work has been supported by the project No. FSI-S-23-8163 funded by The Ministry of Education, Youth and Sport (MEYS, MŠMT in Czech) institutional support and by the research the project RCI (reg. no. CZ.02.1.01/0.0/0.0/16_019/0000765) supported by EU.

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