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Haptic device embedded in rotorcraft seats for target acquisition and tracking tasks

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Abstract

The goal of this work is the development of a haptic feedback device to be embedded in a helicopter seat and to be tested in a rotorcraft flight simulator, as an auxiliary tool to provide cues for pilots while performing target acquisition and tracking tasks.
Based on the literature review, it is expected that a feedback system which doesn't utilise the visual channel can improve a pilot's performance. The proposed haptic system provides a stimulus on the back of the pilot, with an intensity that is proportional to the magnitude of error. Experiments have been performed with pilots and other subjects in a rotorcraft simulator to assess the effect of such feedback. The participants were asked to follow a target position with both the cyclic and the collective lever. Target position and current position of cyclic control were shown on a screen, while collective was communicated with combinations of visual and haptic feedback.
Multiple configurations and control strategies for the haptic feedback were tested and compared to improve the device performance. The results highlighted that communicating the direction of error is an important information for the participants, and could be improved by using a feedback signal with specific properties. Overall the results show that visual information outperformed haptic, however, participants reported its utility as a support system to the visual aids.

1. Introduction

The rising interest in virtual and augmented reality systems together with their technological improvement, shows its impact also in the Aerospace industry. The implementation of augmented reality headsets and cockpit displays can provide pilots with any critical information without diverting their attention from the surrounding environment [1] [2]. However, the complexity and the potential information overload associated with these visual interfaces generate concern about the pilots' workload and their ability to prioritize relevant data at critical moments.
Especially in helicopter flight, it is very common to have a large amount of data that needs to be gathered and processed in a limited time. During emergency maneuvers or in the event of a malfunction, pilots are overwhelmed by visual and audible signals and have to switch attention back and forth between tasks. This can lead to sensory saturation and perceptual errors with subsequent spatial disorientation and loss of situational awareness.
Even though vision is unquestionably the most important and developed sense for humans, most human perceptual experiences involve more than one sensory channel. The ability to perceive information when expressed through multiple senses is essential to improve the management of large and complex data sets without increasing mental strain.
One way to improve the pilot's situational awareness is to exploit alternative sensory channels to increase data availability without overloading vision and hearing. To this end, haptic and tactile displays have shown good results in both simulation and operational applications [3].
Haptic displays are interfaces that convey information through the sense of touch. Tactile cues have been proven to be effective in the helicopters' human-machine interaction in various applications [4] [5]. However, studies are still underway to determine the best use and which cue is best for which application. From vibrations to soft-stops to force feedback systems, many different types of haptic displays have been shown to be well suited for assisting the pilot in high workload environments. Informing and alerting the pilot through tactile receptors reduces the need to look at the

instruments, provides workload benefits, improves handling, and limits commands' overrides [6] [7][8].

In referenced literature concerning haptic devices, the stimulus is affecting the hands of the user. This is a natural choice due to hands' sensitivity to touch, and them being the body part interacting with *all* rotorcraft controls with the exceptions of pedals. The study undertaken in this work investigates a new design for the engagement of under-exploited body parts, i.e. the back. The hope is that the benefits of using a sensory channel free from other information will be further augmented by choosing a skin region that is not used in any control tasks. The device described in this paper is built with a cost-effective design and is not linked to any specific aircraft architecture. The purpose is to generate a cue that is easy to understand and produces a rapid and instinctive response. This display is not tied to a specific application and can be used also in different mission task contexts.

2. Background

Tactile displays are not a new concept for the Aerospace industry, they have been widely studied for security and handling improvement. The possibility to provide cues through the sense of touch has been known since the 1950s. In 1954 Ballard and Hessinger [9] analyzed the benefits of using mechanical tactile interfaces to transmit information about the aircraft state variables through the pilot's hand. In 1961 Hirsch [10] studied the potential of vibratory stimuli and tactile perception to replace auditory and visual means. Hirsch stated that haptic displays could be used on military aircraft for urgent signals that must be immediately translated into action and could not be done with sufficient rapidity by visual or auditory means. The increasing need to relieve the overburdened visual and auditory sensory channels led researchers to consider and further explore the cutaneous sense. However, most of these works had to face the technological limitations of the time and did not progress beyond the proposal or testing stages.
In the 1970s a more mature state of the technology allowed tactile communication devices to be successfully designed and marketed. The most common cutaneous tactile communication methods were vibro-mechanical and electrical systems. Electro-tactile devices allowed a more acceptable structure to be used in the cockpit thanks to the reduced weight, higher reliability, and potential integration with avionics as demonstrated by Zlotnik et al. [11].
An important aspect of haptic displays is that they can be used simultaneously with visual and auditory stimuli. Several studies have demonstrated the benefits of using haptic and visual stimuli together rather than separately. For instance, Anil K. Raj et al. [12] suggested that reaction times are significantly fastest for the combined visual/vibrotactile display with no significant increase in error rate over the visual-only condition, even though the vibrotactile-only display shows a higher error rate.
More recently, the US Navy has developed the Tactile Situation Awareness System (TSAS) program as part of an effort to reduce aviation accidents caused by the loss of SA. The program has designed and tested a series of uniform tactor arrays and has been shown to be effective as an instrument display method for improving performance and reducing pilot workload during the simulation of complex three-dimensional tasks. The same results have been achieved in actual test flights with both fixed and rotary wing aircraft by Olson et al. [3]. Torque protection systems have proven to be ideal candidates for the integration of haptic cues. Torque limitation is one of the most important constraints in helicopter flight, and coupling with the collective is slow dynamic and nearly proportional, so a simple tactile cue is very effective. In 1995, Howitt [13] showed that the use of an automatic flight control system with a soft-stop on the collective could reduce the number of torque limit overshoots and result in better handling.
Further developments in this field were obtained with the introduction of neural networks [14]. The use of neural networks trained to predict flight limit envelope parameters added rapid state prediction to the existing tactile cueing systems and allowed to exploit them not only for pre-designed applications but also in the occurrence of unexpected events.

Using the sense of touch via tactile displays for warning, navigation, surveillance, and situational awareness can potentially make flying more intuitive, safer and less demanding. Nevertheless, there is still space for experimenting with alternative methods and architectures to explore these systems and their potential.

3. Methods

This paper describes the development of a haptic feedback device to be embedded in a helicopter seat to provide cues that guide the pilot in controlling the collective command towards a predetermined target. The system is mounted on the seat's backrest, and the stimulus that it generates on the pilot's back is related to the distance of the actual collective position from the target. The aim of this study is to evaluate the effects of using such a haptic display setup on task accomplishment performance in terms of overall accuracy and workload.

Two kinds of tactile stimulation are investigated in this work. The stimulus obtained with the first method is obtained by the deformation of the seat toward the pilot's body. The information regarding the distance between the collective position and its target is conveyed by pushing a rigid object through the seat cover to locally increase the pressure on the back. The distance is linearly related to the magnitude of the error, up to a maximum deformation.
The second method is based on a different approach. The haptic cue delivered to the pilot consists of a bi-directional pulsed signal. In this case, the pressure applied to the user's body, for a constant error in the tracking task, is a pulsed deformation with a fixed amplitude. The frequency and the direction of the pulsed signal are linked respectively to the magnitude of the error and the direction of the corrective action needed on the collective stick.

4. Prototypes' description

The prototypes described in this section consist of a dual cam-shaft, driven by a bipolar stepper motor attached to the back of the seat of a helicopter's simulator. The behavior of the motor is controlled with an Arduino Mega board and a digital stepper driver. The electric power to the motor was limited at 23 W to keep it from overheating, while the micro-step resolution was found empirically, by setting the highest resolution for which there are no skipped motor steps during operation. In order to provide a consistent positioning, a limit switch was added to the camshaft, allowing it to return to a known position on board reset. The control board receives data through a serial port over a USB cable. To simplify the operation, the sent command is a relative value between 0 and 1 signifying a fraction of the maximal feedback value that should be reached at this moment. The motor speed was limited in the board's firmware to 1.6 revolutions per second. This value limits the rate of change of feedback value with the first method and the maximum feedback value for the second method.
For the purpose of this study, the aforementioned device is mounted on the FRAME Sim fixed base rotorcraft flight simulator at the Department of Aerospace Science and Technology (DAER) of Politecnico di Milano, in Figure 1. The simulator replicates the flight controls of a real helicopter, it includes a cyclic lever, a collective lever, and pedals. The cockpit mockup is equipped with two LCD screens, positioned in front of the pilot, which were used in this study to show the visual feedback.

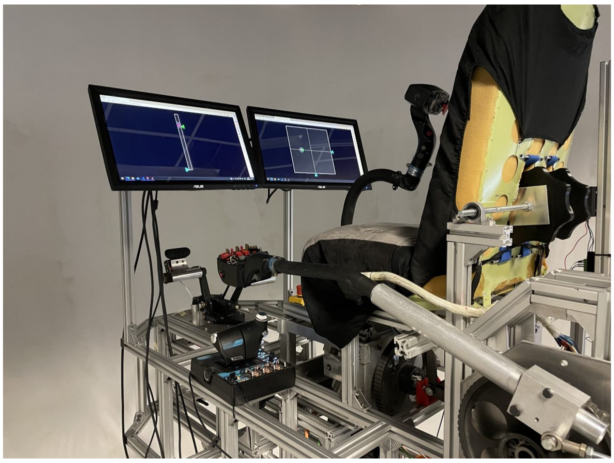

Figure 1: Photo of used simulator setup with the seat, controls and flat displays visible.

The response of the motor to the collective lever's motion and the shape of the cams determine the specific characteristics of the haptic signal. In this paper, the architecture of the prototypes is selected according to the desired haptic feedback to be provided, based on the specific method to which they refer.

4.1 First Method Configuration

The shape of the cam is designed to associate with each position of the motor a deformation of the seat. As already mentioned, the purpose is to generate a deformation of the seat proportional to the received input. For this method, the collective error produces a proportional rotation of the motor. In order to create the desired stimulus, the shape of the cams must correlate an increasing angle of rotation of the motor with increasing deformation.
The shape of the cam is shown in Figure 2. The radius of the cam linearly increases around the profile. The maximum radial dimension of the cam, which corresponds to the maximum intensity of the stimulus, is empirically set to 100 mm, for the given seat. The minimum radius is 60 mm and is associated with the condition of no haptic feedback and nil

angle of rotation of the motor. The increment rate is dictated by the total angle of rotation set for the prototype (180°). This last choice is made to obtain an acceptable resolution and speed of the rotation changes feedback.

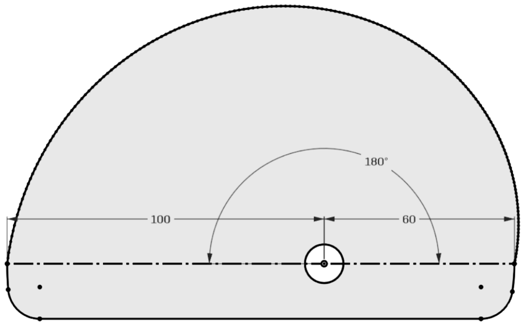

Figure 2: Sketch of the linear positional cam profile demonstrating dimensions used to define the profile.

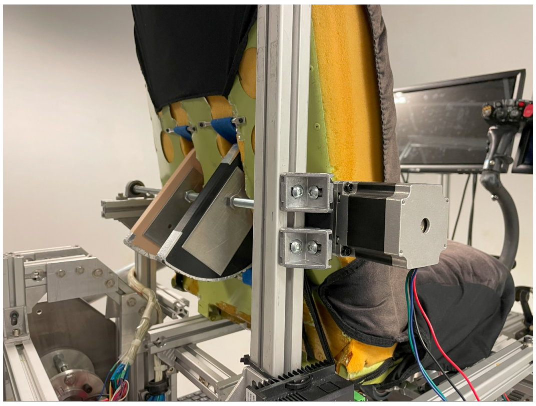

Figure 3: First Method Prototype.

4.2 Second Method Configuration

The stimulus generated with the second method is a bi-directional repetitive signal. The parameters that generate the motor's input signal are the magnitude of the error and its sign. The absolute value of the tracking error of the collective lever is used to regulate the motor's speed. The higher the distance between the collective position and the collective target, the higher the angular velocity of the motor and the cams. Depending on the sign of error, the motor is rotating in different directions, creating a feeling related to the corrective action needed to be taken. For example, if the position of the collective lever is too high, relative to the target, the motion of the cam against the user's back is directed downwards, communicating to lower the lever.

To obtain a tactile stimulation that can communicate its direction, a cam with multiple protrusions was designed. With the rotation of the motor at a given velocity, this cam stimulates a feeling of objects rolling across the back of the user. With a lower number of protrusions and a smaller radius, the signal is more clear and intense. On the contrary, a smoother shape increases user comfort while in contact with the device. As a result of this trade-off, the used geometry shown in figure 4, had 8 protrusions with an outside radius of 75 mm, rounded with radius 10 mm. Figure 5 shows the actual Camshaft involved in this configuration.

The ability to communicate the direction of the corrective action is an important feature of this stimulator design. During the first round of experiments using this setup, it was found that it becomes difficult to discern specific protrusions of the cam for large angular velocities of the shaft. The sequence of protrusions passing over a given region of skin at a frequency up to 12 Hz was creating a feeling of vibration more than individual objects moving in a direction. Because of that, the subjects would sometimes misinterpret the cue and react in the wrong direction. Since the feedback signal was already at maximal value, they would get no change in perceived error, leading to confusion.

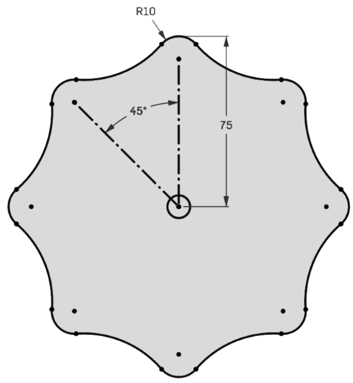

Figure 4: Sketch of the rolling cam profile demonstrating dimensions of the surfaces interacting with the user.

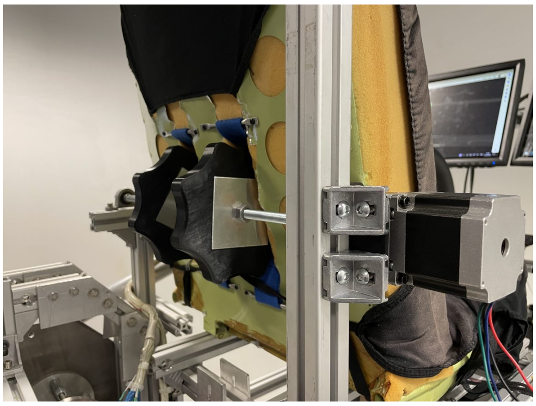

Figure 5: Second Method Prototype.

However, lowering the gain of feedback relative to error magnitude, made closely following the target more difficult due to small differences in stimulation. This issue was improved by changing from a linear slope that is saturated when the error reaches 20% of full collective travel, to a logistic curve, described with equation 1, where x is the error of collective position relative to the full travel of the lever. This created an output signal which doesn't get saturated for possible error values, contrary to the original linear feedback, shown in Figure 6. This way, regardless of the error magnitude, the user receives an immediate response if they are getting closer or further from the target.

$$f_{output}(x) = \left(\frac{e^{7.5x}}{e^{7.5x} + 1} - \frac{1}{2} \right) \cdot 2 \tag{1}$$

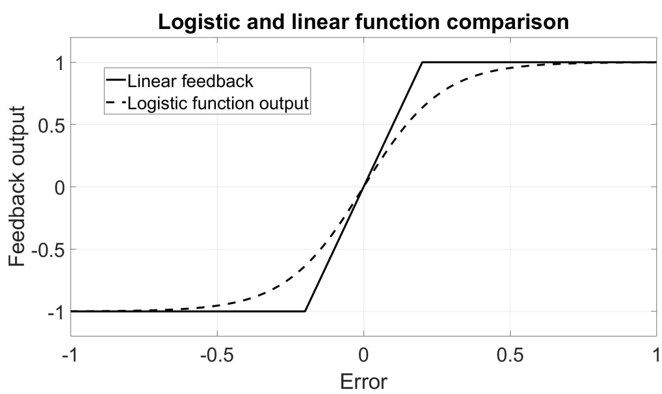

Figure 6: Haptick feedback signal.

5. Experiment

The aim of the experiments is to assess the effectiveness of this haptic feedback both alone and combined with the equivalent visual information.
The experiments are run on the simulator's computer and all the components of the haptic device are fixed to the simulator's base structure. The simulation developed for testing the haptic device includes the generation of two unpredictable target trajectories for cyclic and collective inceptors movement. The monitors provide the participants with the current location of commands and targets. The haptic feedback is related to the tracking performance of the collective lever and aims to provide the same kind of indication reported by the graphic interface for that command.
The trials are conducted with and without the engagement of the haptic feedback and combining visual and haptic aids for tracking the collective. The performance of each trial is evaluated from the accuracy of the targets' tracking and the participants' subjective opinions assessed using the NASA-TLX rating procedure.

5.1 Experiment Setup

The work presented in this paper intends to provide experimental data on the performance of a prototype for the generation of haptic cues that supports, and partially substitute, visual aids. Visual interface design is thus a key factor for testing this haptic system. The graphical interface involved in the simulation, shown in figure 7, is implemented using the Python package `lidia`[1] developed by one of the authors. During the trials, only a control view was utilized, where information for cyclic and collective inceptors was shown on the two 20-inch LCD displays. For each command, the target position is shown with a magenta star symbol, and the current command value with a symbol changing between green, yellow and red depending on the current magnitude of the error. The error magnitude corresponding to each color change is additionally shown with dotted lines around the target position.

Figure 7: Screen capture of visual feedback shown during the experiment. In this example, the collective lever is slightly higher than the tracked target, shown with a green triangle on the left screen, while cyclic control is right of the target, shown with a yellow circle.

The design concept of the task trial lies in its randomness. To realize a random movement of the target, a Simulink module integrated into MATLAB 2022a was utilized to generate and output the signals related to the target movement. Several parameters control the movement of the target and boundaries. For target movement, the adjustable parameters include motion speed, direction, duration, stance duration, maximum position, and task duration. Random target motion parameters were set within certain limits. Figure 8 shows an example of one-axis target movement. Random seeds were utilized to generate reproducible random signals. By selecting a sequence of random seeds, the participants would individually experience a set of unpredictable random tasks, while tasks were consistent among all the participants.

The simulation implemented for these tests involves a random motion of the collective and cyclic targets. The cyclic target's and indicator's longitudinal motion is constrained. This setup is applied in order to collect data also from non-pilot participants while establishing a meaningful baseline task without the engagement of the haptic feedback. The result is a task that involves the left hand to control the collective moving up and down and the right hand from left to right. In this way, the direction of haptic feedback involves Spatial Compatibility only with the collective motion, in order to enable more intuitive interpretation [15]. Users can visually track the targets from the two displays and adjust

[1] `https://pypi.org/project/lidia/`

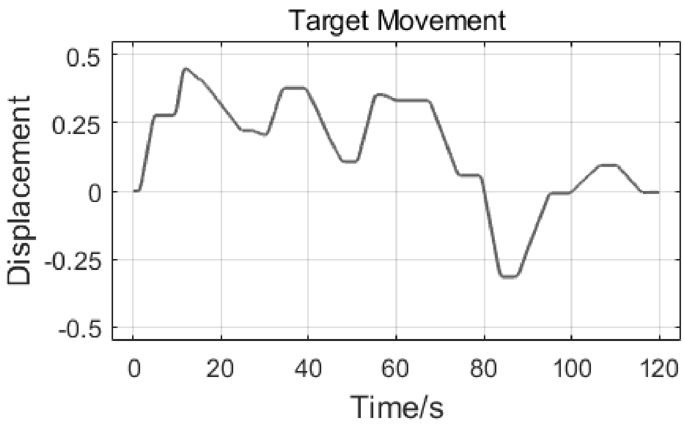

Figure 8: A demonstration of a random target movement task.

both collective and cyclic commands accordingly, or they can rely on the haptic feedback for the collective tracking while focusing their visual attention only on the cyclic motion.

5.2 Testing Methodology

In the early stages of the prototype's development, 5 participants were selected among students and professors. The participants performed two tests, each of which involved three simulations with different configurations. During the first simulation users are provided with visual information only (labeled "V"). Compared to a typical helicopter cockpit, the amount of visual information present in the trial is very low. To increase the participant engagement in the visual task, the collective indicator is displayed on the left screen while the cyclic indicator is on the right screen, see figure 7. The second simulation involves the use of the haptic system. In this case, the only visual feedback provided to the user is the cyclic indicator while information for the collective following is given only by the haptic device (labeled "H").
In the third trial, participants are provided with both visual and haptic feedback support (labeled "HV") throughout the whole duration of the simulation.
After the development of the second method and the adjustments to adapt the prototype, the same tests are repeated on the same participants. Finally, based on the results carried out from the initial tests, only the better-performing prototype, which was the second method, is involved in the last testing phase where also the effect on the workload is considered.

6. Results

In this section is presented the selection and processing of data obtained from simulations. Subjects' behavior is recorded in the three configurations and the corresponding tracking performances are compared. The simulation output data used to evaluate the subjects' performance are the controls' position and their target trajectories, Figure 9.

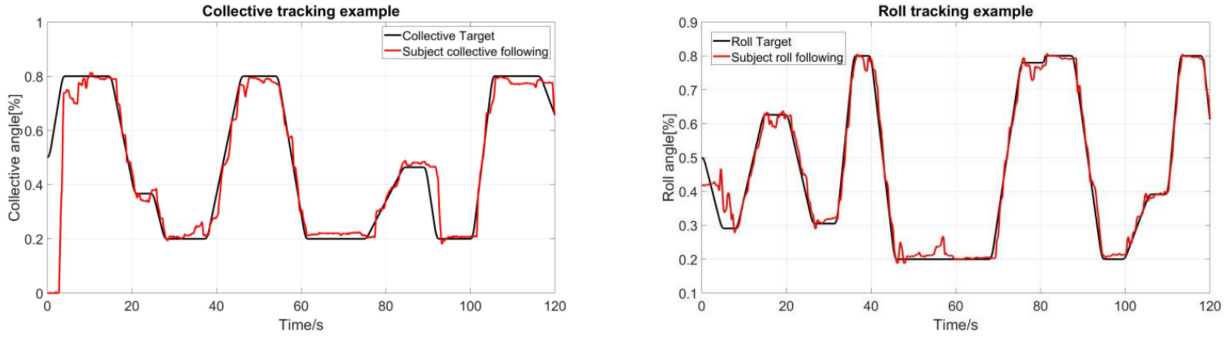

Figure 9: Output data of one of the simulations involved in the tests' performance evaluations.

Each subject performs 2 tests with the 3 configurations. The first test is performed to make the user more familiar with the interface and the task. With the data coming from the second test, the accuracy of the tracking task for each simulation is evaluated with the root mean square error (RMSE) between the targets and actual curves of roll and collective. Finally, for each method, a global evaluation of the overall performance is assessed from the average of all participants' errors. The results of the 5 participants who tried both methods are displayed in this section. The overall results of the tests that involved the first method are displayed in Figure 10 while those referred to the second method are shown in Figure 11. The median and variance of each data set are reported in Table 1 and 2.

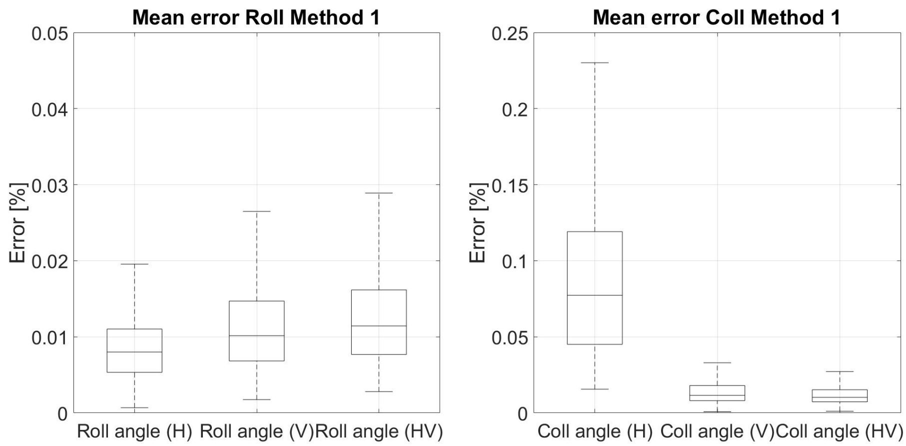

Figure 10: Overall errors of Method 1 Configuration.

Table 1: Method 1 Results

	Roll angle (H)	**Roll angle (V)**	**Roll angle (HV)**	**Coll angle (H)**	**Coll angle (V)**	**Coll angle (HV)**
Median	0.0080	0.0101	0.0114	0.0773	0.0115	0.0102
Variance (σ)	0.0003	0.0006	0.0005	0.0041	0.0020	0.0013

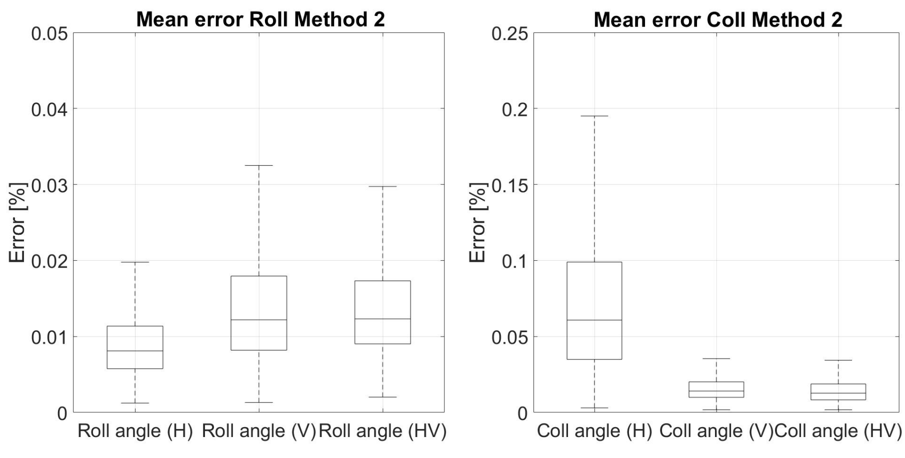

Figure 11: Overall errors of Method 2 Configuration.

Table 2: Method 2 Results

	Roll angle (H)	**Roll angle (V)**	**Roll angle (HV)**	**Coll angle (H)**	**Coll angle (V)**	**Coll angle (HV)**
Median	0.0080	0.0122	0.0123	0.0607	0.0140	0.0127
Variance (σ)	0.0001	0.0002	0.0004	0.0023	0.0009	0.0014

Even though the data obtained in these tests refer to a small group of participants, some preliminary evaluations can be drawn.
The highest collective tracking error is registered in the configuration in which the only aid related to the collective tracking comes from the haptic device. This is true for both methods. The lowest collective tracking error is registered in the configuration that exploits both haptic and visual feedback for the collective tracking. Again, this is true for both methods.
The tracking of the roll target is not directly related to the haptic feedback. Anyway, it is possible to notice that, when the user is provided with both haptic and visual information on the collective tracking, only the first method's prototype causes a significant deterioration in the roll tracking.
These preliminary results suggest that both methods can be beneficial in this type of application when combined with visual inputs. However, more tests are needed to assess further conclusions.

6.1 Comparison between the two methods

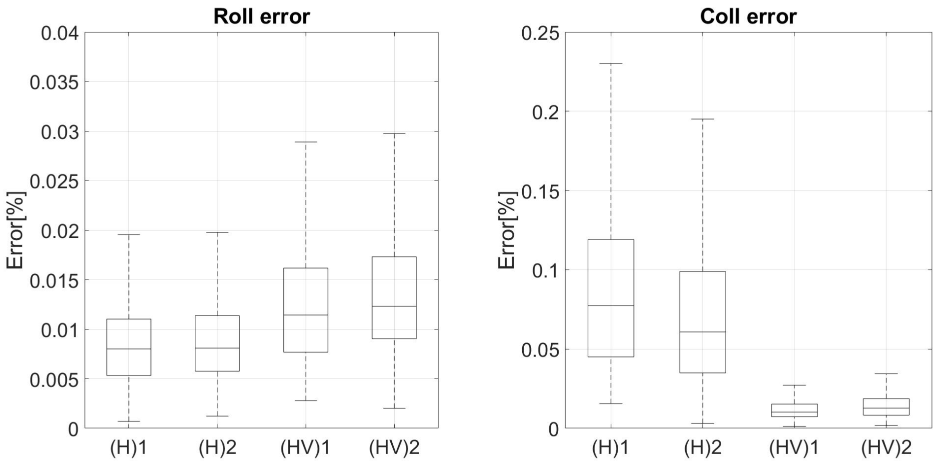

Figure 12: Comparison of the mean errors of methods 1 and 2. The letters between parenthesis (H, HV) indicate the tests' configuration (only those that included the haptic feedback are considered). The numbers(1 and 2) represent the specific method.

Figure 12 exhibits, side by side, the results obtained with the two methods from the same participants. The most relevant data sets are those concerning collective tracking in the configuration with only haptic aids. In Figure 12 these data are labeled as "(H)1" for the first method and "(H)2" for the second method. Comparing the two results it is possible to see a reduction in the tracking error, and thus a better performance, for the second method prototype. The roll's tracking errors and the collective tracking error in the configuration with both haptic and visual feedback are only slightly affected by the specific method, as expected from the experiment setup. As already mentioned, these results refer to a very small group of participants and, although there is a time lag of several months between the two methods' tests, part of the improvement may be related to the subjects' familiarization with the task. However, the participants' feedback confirms the obtained outcome. All the participants stated that the second method was clearer and more useful, especially due to the presence of the direction indication, which is not present in the first method.

6.2 Best Method's Results

In this last testing phase, only the second method is involved, which turned out to be the most accurate and most appreciated among the two. A total of 15 subjects performed the tests and expressed their opinion about the three test configurations ("H", "V", and "HV") using the Nasa-TLX rating scale.
In this case, the order of the tests involving the haptic feedback is not fixed. Half of the participants performed the tests with haptic feedback only before those with haptic and visual aids, and the other half performed them in reverse order.
In addition to the analysis of tracking accuracy, this final phase also includes an analysis of the workload perceived by the participants in the various test configurations.

Tracking Accuracy

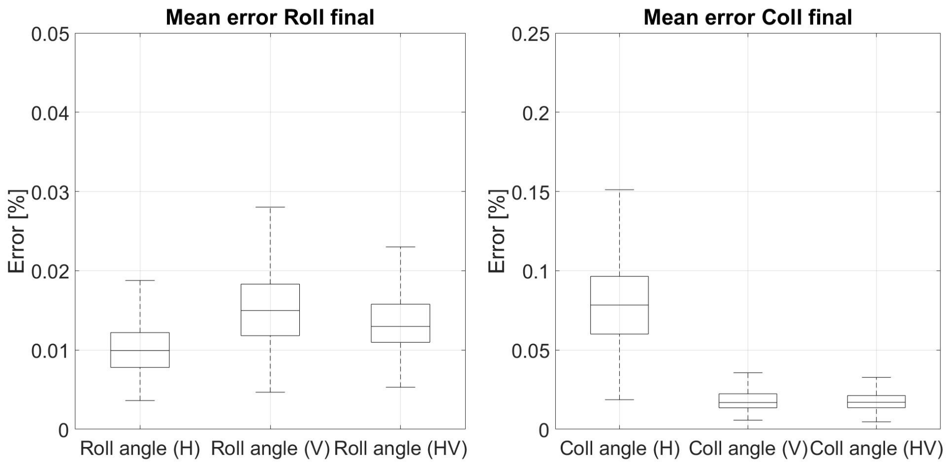

Figure 13: Overall errors of Method 2 Configuration for all participants.

Table 3: Method 2 Results of all participants

	Roll angle (H)	Roll angle (V)	Roll angle (HV)	Coll angle (H)	Coll angle (V)	Coll angle (HV)
Median	0.0099	0.0149	0.0129	0.0783	0.0168	0.0170
Variance (σ)	0.0001	0.0001	0.0002	0.0008	0.0007	0.0008

Figure 13 and Table 3 show the results of the second method prototype referring to the tests of the 15 participants. The outcome of these tests shows that the combination of haptic and visual aids for collective tracking leads to the best results. The error of the collective tracking is comparable to the one obtained in the visual configuration, while roll tracking accuracy is improved.
In the haptic configuration, the error on the collective is too high to be compared to the visual feedback.

Nasa TLX Results

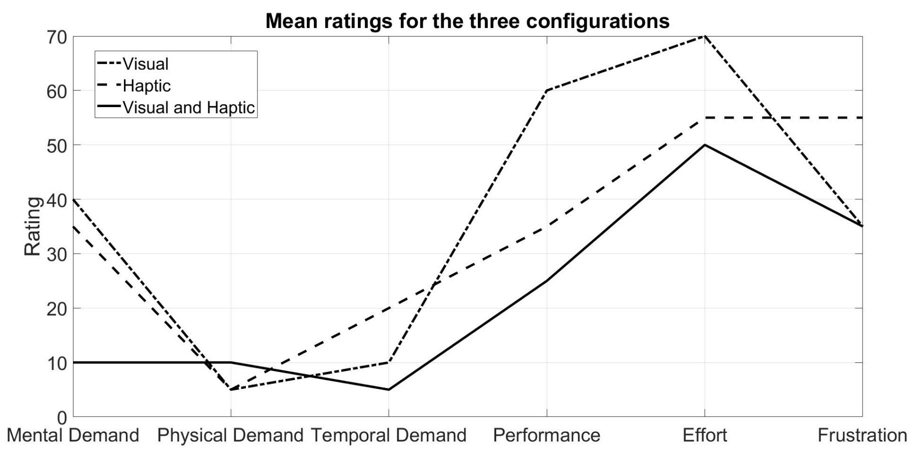

Figure 14: Nasa-TLX mean ratings for the three configurations.

Figure 14 shows the mean ratings of the six parameters used to assess the perceived workload according to Nasa-TLX for the three configurations. Figure 15 and Table 4, report the Overall workload values for all participants in the three configurations.

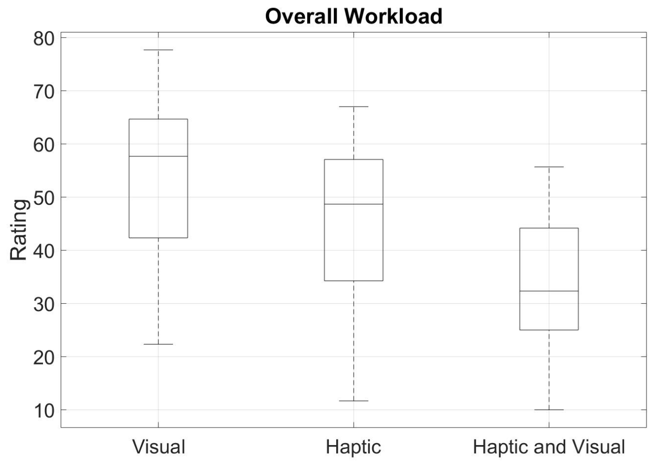

Figure 15: Nasa-TLX overall workload for the three configurations.

Table 4: Nasa-TLX Overall Workload

	Visual (V)	**Haptic (H)**	**Haptic and Visual (HV)**
Median	57.67	48.67	32.33
Variance (σ)	302.15	268.03	197.15

As already mentioned the focus of this study is on the effect of this device on the perceived workload. The data displayed in Figure 14 shows an overall decrease in the mean grades of the individual indices that make up the workload when comparing the Haptic configuration with the visual one. The lowest ratings are referred to the haptic and visual configuration.
Figure 15 and Table 4 confirm this trend and show the overall workload calculated for the three configurations. The best results, both in terms of Overall Workload and tracking accuracy, are obtained with the configuration that exploits the haptic device and visual information combined.

7. Conclusions

The haptic device described in this thesis aims to be a reliable, clear, and effective source of information to indicate to the pilot the correct positioning of the collective without generating intrusive and ambiguous inputs on the control stick. The correct application and functioning of this system allow the pilot to rely on the haptic stimulus to accomplish part of the operations involved in the task. As a consequence, the visual sensory channel is relieved of the piece of information conveyed by the haptic display, which leads to a sensible reduction in the overall workload perceived by the pilot.

This study shows that the haptic feedback generated by this device if combined with the equivalent visual information, is capable to reduce the effort of the user and enhance the overall accuracy in performing a tracking task that involves both collective and cyclic movement. It is interesting to notice that the final prototype has successfully reduced the perceived workload also in the tests that involved only the haptic aid for the collective tracking, although producing poor accuracy results. This outcome suggests that the generated stimulus allows users to respond in an intuitive manner, but in many cases, part of the information (especially the direction of the target) is not clearly perceived. However, it should be considered that all participants had no previous experience with the haptic device, in most cases neither with helicopters simulators, and only performed 4 tests involving this haptic feedback. None of the participants is a pilot, so it was not possible to have a relevant opinion on the possible application of the device in actual flight.

8. Acknowledgments

The authors wish to thank all the staff working in the FRAME Sim Laboratory at the Department of Aerospace Science and Technology of Politecnico di Milano for their support in the development of this work.

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