

# Evaluation of Haptic Shared Control and a Highway-in-the-Sky Display for Personal Aerial Vehicles

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Highway-in-the-sky displays and haptic shared control could provide an easy-to-use control interface for non-expert pilots. In this paper, various display and haptic approaches are evaluated in a flight control task with a personal aerial vehicle. It is shown that a tunnel or a wall representation of the flight trajectory lead to best performance and lowest control activity and effort. Similar results are obtained when haptic guidance cues are based on the error of a predicted position of the vehicle with respect to the flight trajectory. Such haptic cues are also subjectively preferred by the pilots. This study indicates that the combination of a haptic shared control framework and highway-in-the-sky display can provide non-expert pilots with an easy-to-use control interface for flying a personal aerial vehicle.

## I. Introduction

Within the European Union, a Personal Aerial Transportation System (PATS) has been presented as a potential solution to problems associated with predicted volumes of traffic of the future.<sup>1</sup> The European project myCopter<sup>a</sup> investigates enabling technologies for such a transportation systems.<sup>2</sup> Apart from the socio-economic aspects of a PATS, autonomous flight capabilities of Personal Aerial Vehicles (PAV) (such as vision-based localization, swarming and collision avoidance), and handling qualities and training requirements for PAVs, the project also studies novel technologies for human-machine interfaces (HMI). In the context of a PATS, users should be able to control their PAV with a minimum amount of training, and the interface between the pilot and a highly augmented PAV should provide the pilot with continuous feedback while the pilot remains in control.

Control interfaces for vehicular control in aerospace systems are predominantly focused on two opposing approaches: manual control and automation. Automation can be used to overcome disadvantages of manual control, but can also have undesirable effects, especially during control of more safety-critical dynamic processes in unpredictable environments.<sup>3</sup> The use of automation can also lead to loss of skills, and it has been argued that human errors due to loss of skills or over-reliance on automation could lead to a vicious circle of increased regulations that take away more responsibilities of the human, which in turn leads to increased loss of skills.<sup>4</sup>

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<sup>a</sup><http://www.mycopter.eu>

Therefore, it has been proposed to combine the advantages of manual control and automation in a system where the human and automation continuously share control through force interactions on a control interface: haptic shared control.<sup>3</sup> The human and automation both exert forces on the control inceptor, and its position provides input to the controlled system. Such a system would allow the human to interact with automation directly and overrule it if necessary. In this way, the human retains ultimate control authority. It has been shown that such systems can result in increased performance in vehicular control tasks.<sup>5,6,7</sup>

An alternative way for informing a pilot about his control task is to include additional information in the visual display. Current displays, such as the Primary Flight Display, combine information about the current aircraft state and the target that the pilot has to follow in single view. On the contrary, perspective cues on the future path, such as provided by a tunnel-in-the-sky or highway-in-the-sky (HITS) display, are not presented. Displays with perspective cues have only recently found their way into the cockpit of general aviation aircraft, and have been shown to enhance pilot performance in the task of flight guidance.<sup>8,9,10</sup>

The goal of this paper is to investigate whether the combination of a haptic shared control framework and a HITS display could result in an easy-to-use control interface and better performance for non-expert pilots. These novel control interfaces are integrated with a dynamic model for a PAV, which is developed within the myCopter project. Subsequently, this setup is evaluated experimentally to assess to which extent participants without formal flight training benefit from haptic cues and enhanced visual information.

## II. A control task for personal aerial vehicles

Within the context of the myCopter project, PAV pilots will have limited flight experience. A highway-in-the-sky display and haptic shared control system need to be integrated into a control task that can be performed precisely and without much training. In this section, the flight control task is detailed. First, the PAV dynamic model is introduced. After that, the HITS display and haptic shared control architecture are described.

### II.A. Dynamic response of a personal aerial vehicle

One of the goals of the myCopter project is to develop handling qualities guidelines and criteria for PAVs. Conventional rotorcraft response types, such as rate-command attitude-hold, are unsuitable for prospective PAV-pilots with minimal flight training. Therefore, a generic PAV dynamics model has been implemented by the University of Liverpool such that response type requirements can be identified for varying levels of flying skills, in order to ensure safe and precise flight.<sup>11,12</sup>

In this paper, the generic PAV dynamics model is used in its so-called *hybrid* mode. In this mode, the dynamic response in forward flight corresponds to attitude-command attitude-hold (ACAH) in roll, acceleration-command speed-hold (ACSH) in pitch and rate-command attitude-hold (RCAH) in heave. Each of these degrees of freedom is independent from the others. This configuration results in Level 1 handling qualities, which makes it the most suitable for non-expert pilots controlling PAVs.<sup>12</sup>

For this research, the control task is limited to the roll degree of freedom. The longitudinal and vertical degrees of freedom of the PAV are controlled by an autopilot. The speed of the PAV was fixed at 50 knots.

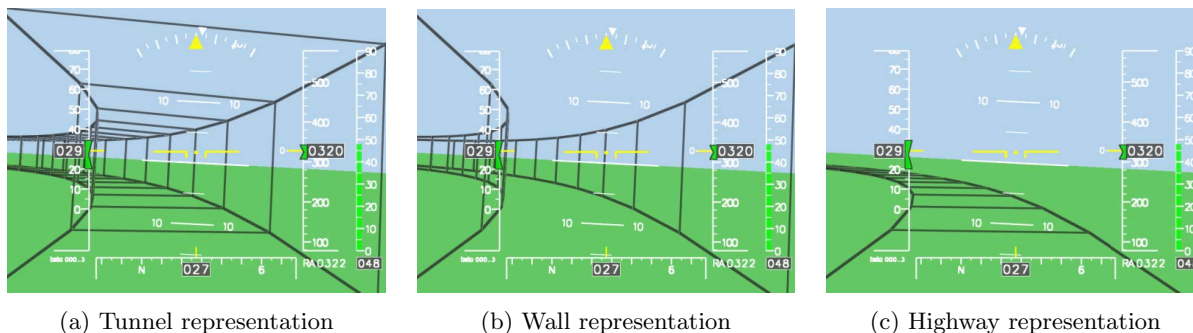


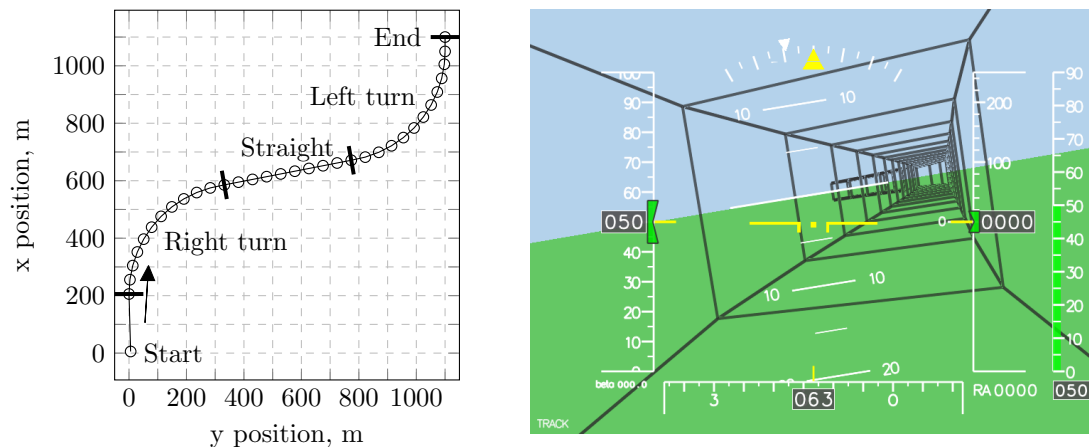
Figure 1: Various representations of a flight trajectory in a Highway-in-the-Sky display (developed by the German Aerospace Center DLR).

## II.B. Highway-in-the-sky display

Within the myCopter project, a highway-in-the-sky display (HITS) has been developed by the German Aerospace Center DLR that can display the perspective information of a flight trajectory. The myCopter HITS shows a three-dimensional tunnel trajectory on a modified Primary Flight Display (PFD), which can help the pilot in following a specific trajectory. Additionally, target indicators for parameters like altitude, airspeed and attitude can be displayed on the PFD. The tunnel trajectory can be represented in various ways, see Figure 1. The most common representation consists of an enclosed tunnel (Figure 1a). A configuration that only shows the walls of the tunnel is preferred by test pilots from DLR (Figure 1b). A novel way of representing the tunnel trajectory is equivalent to a highway, which would be the most common representation for pilots without formal flight training but with car driving experience (Figure 1c).

For the control task in this research, a flight trajectory is generated according to a circle-line-circle approach.<sup>13</sup> These trajectories connect a starting point with an end point through a turn with a predefined radius, a straight section, and another turn, respectively. The radius of the turn can be calculated according to the speed of the PAV and a maximum bank angle. Any changes in altitude between the start and end of the flight trajectory would be performed in the straight section, but in the current task the altitude is kept constant throughout the trajectory.

A schematic representation of the flight trajectory for the control task is shown in Figure 2a. The pilot controls the PAV with a constant speed from a start position through a right turn, a straight section and a left turn to the end of the trajectory. Given that the generic PAV dynamics model has a ACAH response in the roll axis, the pilot can perform the turns with a constant lateral input on the control inceptor. The pilot would perceive this flight trajectory as shown in the HITS display in Figure 2b. The tunnel dimensions are 40 m horizontally and 30 m vertically and the tunnel gates are placed at equal distances.



(a) The trajectory represented in the horizontal plane

(b) The trajectory in the HITS display at the end of the right turn

Figure 2: The flight trajectory for the control task.

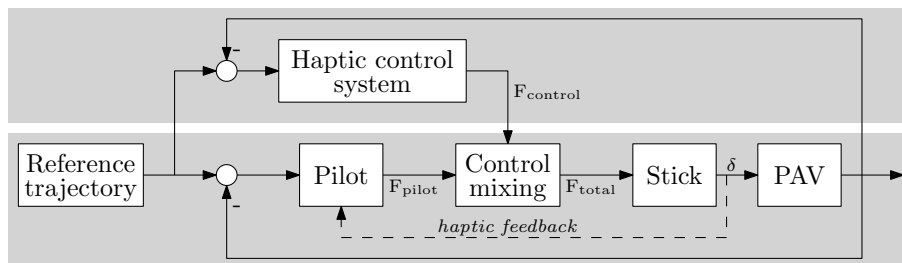


Figure 3: A haptic-shared control architecture.

### II.C. Haptic shared control

In haptic shared control, the human and an automatic control system continuously share control authority through force interactions on the control inceptor.<sup>3</sup> These forces can guide the user along a certain optimal trajectory. Additionally, the forces can indicate operational boundaries of the controlled system. The architecture of haptic shared control used in this paper is presented in Figure 3. In this architecture, a human pilot is tasked with following a reference trajectory while a haptic control system provides guidance forces on the control inceptor. The influence of the guidance forces from the haptic control system are limited in magnitude, such that it can be ensured that the human can always choose to overrule the haptic control system.

The haptic forces are calculated according to the geometrical relation between the predicted position of the PAV with respect to the flight trajectory. Prediction of the future position of the PAV is used to mimic look-ahead behavior of pilots. This relation is schematically shown in Figure 4.

The current position of the PAV is represented by  $p$ . The predicted position  $p_{\text{pred}}$  is calculated as follows:

$$p_{\text{pred}} = p + V_{\text{PAV}} \cdot t_{\text{pred}} , \quad (1)$$

in which  $V_{\text{PAV}}$  presents the current velocity vector of the PAV and  $t_{\text{pred}}$  the prediction time.

The error of the predicted position with respect to the flight trajectory  $e$  is calculated through geometrical relations between a point and a line in three dimensions, see Figure 4. The error  $e$  is then projected onto the PAV body reference frame and decomposed into its horizontal and vertical components ( $e_{\text{hor}}$  and  $e_{\text{vert}}$ , respectively). In this way, the error of the predicted position is related to the different independent degrees of freedom of the PAV.

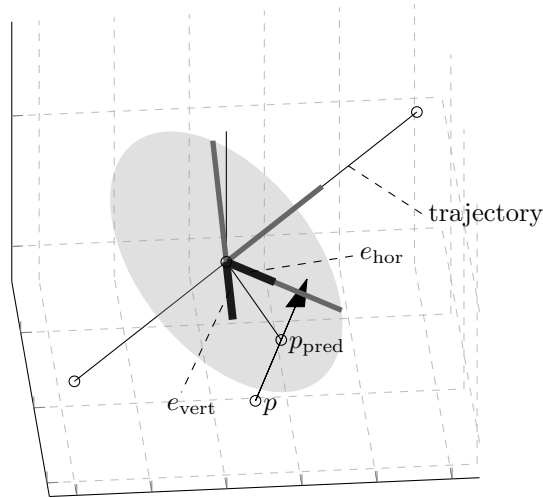


Figure 4: Determination of the horizontal and vertical error of a point with respect to a flight trajectory.

In this control task, pilots do not have to control their altitude and speed, and only have to use the roll axis of the control inceptor to follow the flight trajectory. The haptic forces are proportional to  $e_{\text{hor}}$ :

$$F_{\text{roll}} = \begin{cases} F_{\text{max}}/10 \cdot e_{\text{hor}} & \text{if } -10 \leq e_{\text{hor}} \leq 10 \\ F_{\text{max}} & \text{if } e_{\text{hor}} > 10 \\ -F_{\text{max}} & \text{if } e_{\text{hor}} < -10 \end{cases} , \quad (2)$$

in which  $F_{\text{max}}$  represents the maximum force that can be generated by the haptic control system. This is set to 2.5 N to prevent the system from exerting forces that are too high for the pilot to counteract comfortably. At the same time this ensures that the pilot needs to be engaged during the entire control task, as the haptic control system can not follow the flight trajectory automatically.

### III. Experimental evaluation

The control task described in Section II was evaluated experimentally. The experimental design and results are presented in this section.

#### III.A. Experiment design

##### III.A.1. Conditions

The experiment was designed to evaluate whether the combination of a haptic shared control framework and a HITS display could result in an easy-to-use control interface and better performance for non-expert pilots. The three HITS display configurations as shown in Figure 1 were evaluated: a tunnel representation, a wall representation and a highway representation of the flight trajectory. Furthermore, a condition without haptic guidance was tested, as well as three values for the prediction time of the haptic cues  $t_{\text{pred}} = 0, 1.5, 3$  s. The experiment had a full  $3 \times 4$  factorial design, which resulted in 12 experimental conditions.

##### III.A.2. Apparatus

The experiment was performed on a fixed-based simulator that consisted of a VIEWPixx display from VPixx Technologies Inc., USA, with a refresh rate of 120 Hz and a electrical control-loaded sidestick from Wittenstein Aerospace & Simulation GmbH, Germany. The HITS display, see Figure 2b, was shown on the display that was located 1 m in front of the participants. The sidestick had a maximum deflection of  $\pm 14$  deg and did not have a breakout force. The pitch axis of the sidestick was kept a zero position. The stiffness in the roll axis was set to 1 N/deg.

##### III.A.3. Participants

In total, ten participants performed the experiment, of which three were female. Their age ranged between 23 and 35. None of the participants had formal flight training, although some were familiar with manual control tasks in flight simulators. Before the experiment, participants were briefed about their task. They were informed that they would experience different haptic support cues, but were not told about the underlying algorithms. Participants were asked to follow the center of the tunnel trajectory in the HITS display as accurately as possible.

##### III.A.4. Procedure

The experiment had a within-participant design in which all participants performed all twelve conditions. As the experimental control task was rather easy, participants only performed 1 or 2 training trials to familiarize themselves with the PAV dynamics and the HITS display. During the experiment, the order of the conditions was based on a Latin square design such that the conditions were presented quasi-randomly. Participants were not told which condition was presented and performed three experimental trials for each condition. Each trial lasted 70 seconds in which participants traversed the entire flight trajectory. Participants all completed the experiment within 75 minutes. Data were logged at 100 Hz.

#### III.B. Results

Various dependent measures were recorded during the experiment. The root-mean-squared value of the horizontal error signal  $e_{\text{hor}}$  is used as a measure for pilot performance. The variance of the lateral input signal  $\delta_{\text{lat}}$  indicates the control activity of the pilots. Finally, the variance of the lateral input force  $F_{\text{lat}}$  serves as a metric for pilot effort.

The measured data were averaged over all trials and all participants to reduced the variance of the dependent measures. The error bars in the results represent the interval where it is 95% confident that it contains the population mean. These error bars have been corrected for variability between participants by adjusting the participant means for between-participant effects. The measured data are presented separately for the different segments of the flight trajectory.

### III.B.1. Pilot performance

The pilot performance for the flight trajectory is presented in Figure 5. It is clear that the highway representation of the flight trajectory leads to worse performance in following the flight trajectory compared to the wall or tunnel representation when pilots are not supported with haptic cues. When pilots have access to haptic guidance forces, performance is increased as they become better at minimizing the lateral error.

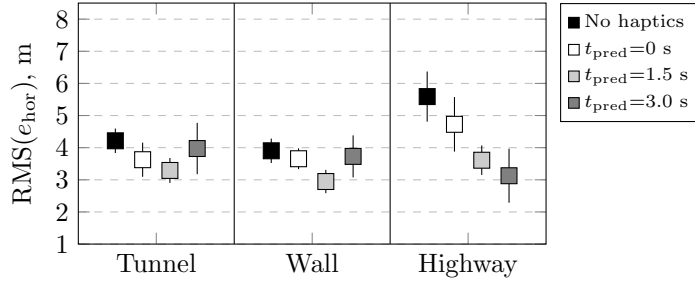


Figure 5: Pilot performance for the entire flight trajectory.

Pilot performance is shown separately for the different segments of the flight in Figure 6. In general, an increase in prediction time  $t_{\text{pred}}$  leads to increasing performance. However, during the final flight segment (the left turn) pilot performance becomes more variable when  $t_{\text{pred}} = 3.0$  s. During the right turn and the straight segment, the haptic cues based on the largest prediction time lead to the best pilot performance and allow pilots to perform the flight control task with a highway representation with similar performance to the tunnel and wall representations.

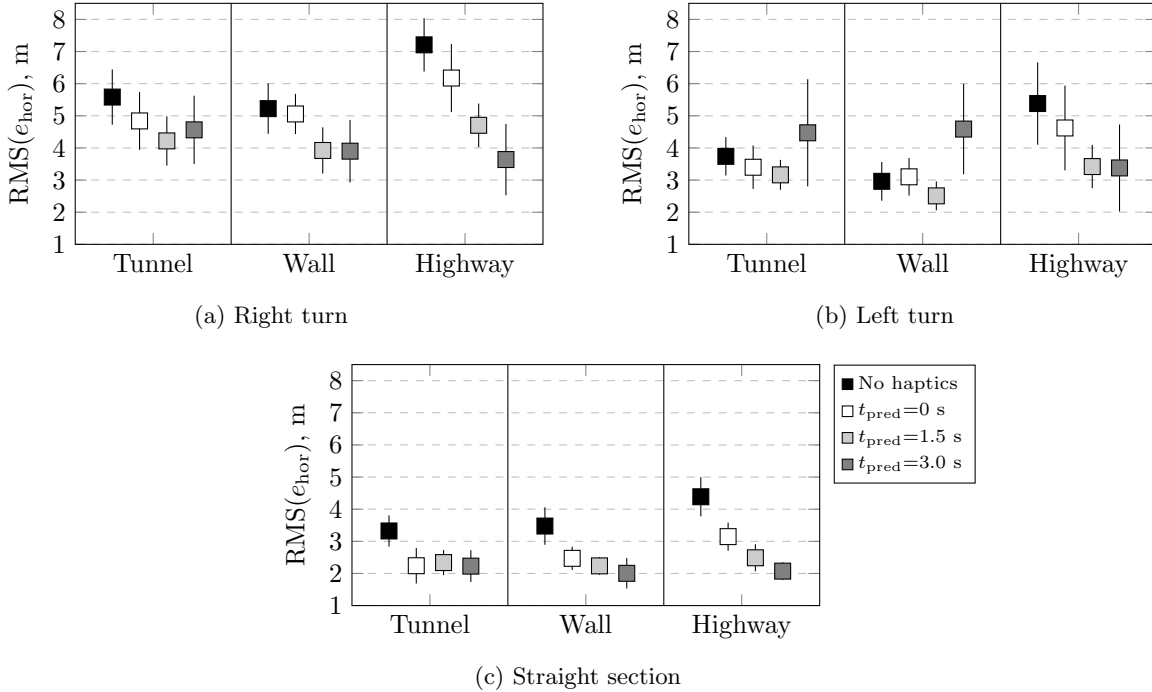


Figure 6: Pilot performance.

### III.B.2. Pilot control activity

The variance of the lateral input signal  $\delta_{\text{lat}}$  is regarded as a measure for pilot control activity. As shown in Figure 7, pilot control activity is very low for this control task, which can be explained by the dynamic response of the PAV. With an attitude-command attitude-hold response it is only necessary to give a constant

lateral control input to perform a turn. During the straight segment, pilots need to keep the sidestick centered. Only small additional inputs are required during the control task to make corrections to the flight path.

Even though the pilot control activity is small for all flight segments, there is a clear influence of the experimental conditions. Control activity tends to be slightly larger for the highway representation. When  $t_{\text{pred}} = 0.0$  s, pilot control activity is increased with respect to the other haptic conditions, which indicates that the haptic cues provided in this condition did not match the pilot's intentions. This is also in-line with pilot comments, which indicated that the haptic condition with a prediction time of 1.5 s and 3.0 s were preferred. In general, control activity attained the lowest values in conditions with  $t_{\text{pred}} = 3.0$  s.

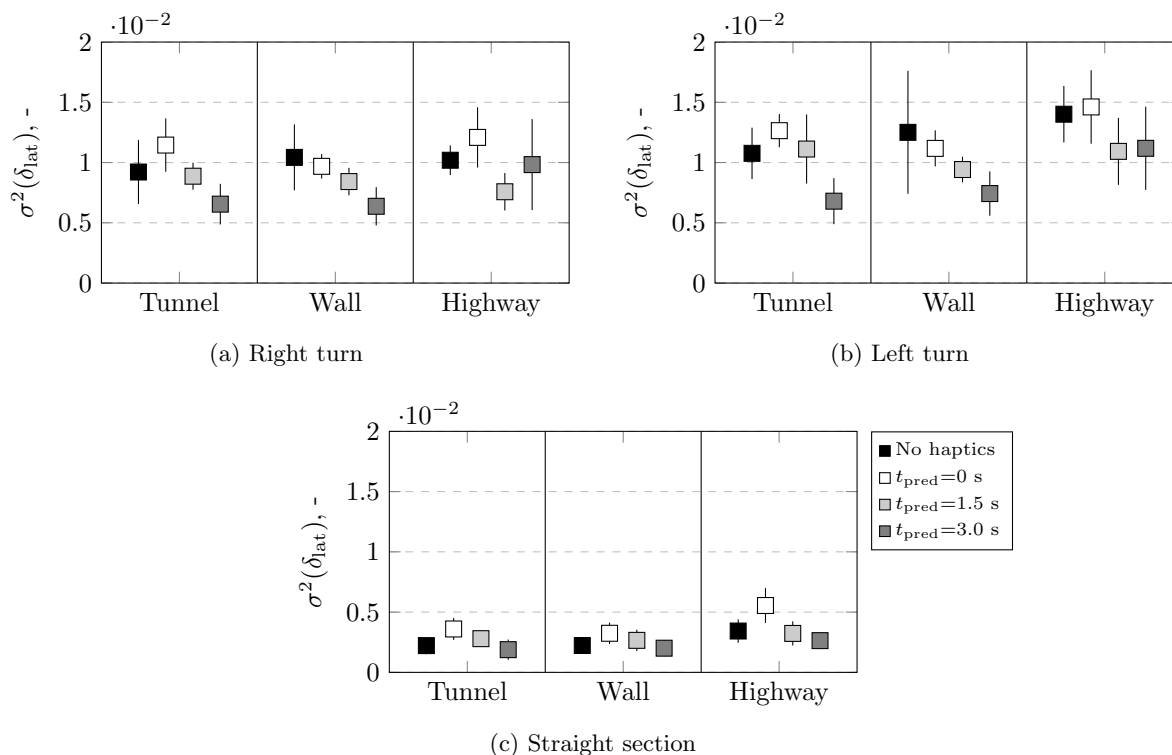


Figure 7: Pilot control activity.

### III.B.3. Pilot effort

Pilot effort was measured through the variance of the pilot lateral input force  $F_{\text{lat}}$  on the sidestick. It is clear from Figure 8 that pilot effort is slightly higher in the turns compared to the straight flight segment. This is consistent with the measure for pilot control activity.

During the turns, an increase in prediction time  $t_{\text{pred}}$  resulted in lower effort with respect to the condition without haptic guidance. However, pilot effort was slightly increased when  $t_{\text{pred}} = 0.0$  s, similar to the increase in pilot control activity found in this condition. This indicates that the haptic cues provided in this condition did not match the pilot's intentions.

In the straight flight segment, any haptic cues resulted in slightly increased pilot effort with respect to the condition without haptic guidance. However, this increase is very small and the resulting pilot effort is still low compared to the effort exerted during the turns.

## IV. Conclusion

An experiment was performed in which it was investigated whether the combination of a haptic shared control framework and a highway-in-the-sky display could result in better performance for non-expert pilots flying a personal aerial vehicle. Various representations of a flight trajectory in a highway-in-the-sky display were evaluated. It was found that a tunnel and a wall representation led to the best performance, whereas a highway representation resulted in worse performance and higher control activity and effort.

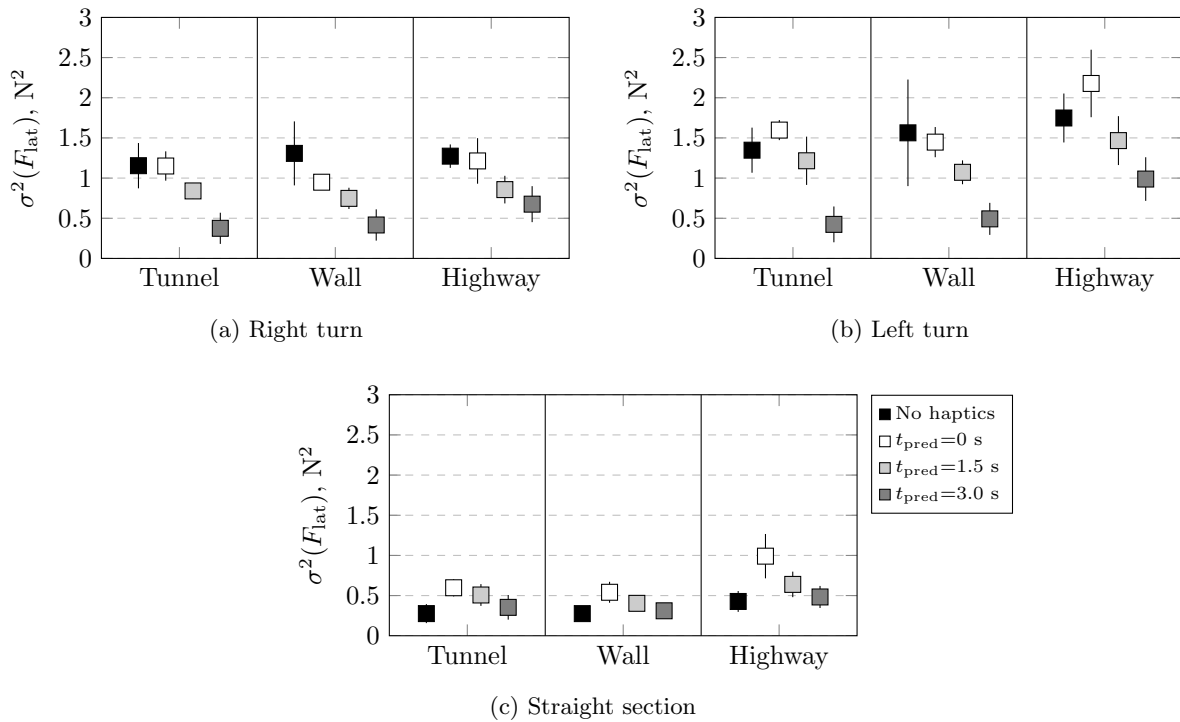


Figure 8: Pilot effort.

Haptic guidance cues on the sidestick allowed pilots to achieve better performance with lower control activity. However, pilots had to increase their control effort when the haptic guidance cues were not based on the error of the predicted position of the PAV with respect to the flight trajectory. Best performance, lowest control activity and effort were attained with the highest prediction time of 3.0 s, which was also subjectively the preferred condition of most pilots.

This study indicates that the combination of a haptic shared control framework and highway-in-the-sky display can provide non-expert pilots with an easy-to-use control interface for flying a PAV. Future work will focus on extending this approach to other degrees of freedom.

## V. Acknowledgments

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