

# An Experimental Comparison of Haptic and Automated Pilot Support Systems

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External aids are required to increase safety and performance during the manual control of an aircraft. Automated systems allow to surpass the performance usually achieved by pilots. However, they suffer from several issues caused by pilot unawareness of the control command from the automation. Haptic aids can overcome these issues by showing their control command through forces on the control device. To investigate how the transparency of the haptic control action influences performance and pilot behavior, a quantitative comparison between haptic aids and automation is needed. An experiment was conducted in which pilots performed a compensatory tracking task with haptic aids and with automation. The haptic aid and the automation were designed to be equivalent when the pilot was out-of-the-loop, i.e., to provide the same control command. Pilot performance and control effort were then evaluated with pilots in-the-loop and contrasted to a baseline condition without external aids. The haptic system allowed pilots to improve performance compared with the baseline condition. However, automation outperformed the other two conditions. Pilots control effort was reduced by the haptic aid and the automation in a similar way. In addition, the pilot open-loop response was estimated with a non-parametric estimation method. Changes in the pilot response were observed in terms of increased crossover frequency with automation, and decreased neuromuscular peak with haptics.

## I. Introduction

Manual control of an aircraft is a difficult task. Pilot's loss of control is the primary cause of fatal accidents for general aviation vehicles, and this happens primarily during phases that require the pilot to

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perform a large number of critical tasks (e.g, landing, maneuvering).<sup>1,2</sup> To improve the safety of flying, pilots need to be supported with external aids that can facilitate the control task.

Automation is defined as “devices or systems that accomplish (partially or fully) a function that was previously carried out (partially or fully) by a human operator”.<sup>3</sup> By delegating complex tasks to automated systems, the control of an aircraft can be simplified. Furthermore, performance of automated systems generally surpass human pilots.<sup>4</sup> A common belief is that safety and performance would drastically increase with a fully automated aircraft, where the automation is able to perform all control tasks without human interaction.<sup>5</sup> However, this is far from being realized. Automation is inefficient when unpredicted changes happens on the external environment, or when a novel decision must be taken.<sup>6</sup> The human operator is needed to supervise the automated system and handle unexpected critical situations.

The presence of human operators gives rise to several issues related to human factors that could happen with an improper design of automated systems. Main issues are the degradation of pilot skills of manually controlling the aircraft, over-reliance on automation and vigilance decrement.<sup>7-9</sup> Furthermore, improper automation could lead to a loss of situational awareness. Situational awareness indicates “the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future”, or, shortly, “knowing what’s going on”.<sup>10,11</sup> With automation, letting pilots know “what’s going on” is a key problem. The most common approach is to provide visual or auditory alerts about automation functionality and failures. However, this approach suffers from a number of pitfalls, like overloading of information and presence of false alarms.<sup>12</sup> Ignoring such issues could lead to severe problems. For example, pilots may require too much time to detect failures of the automation, and they may not be able to recover from these failures.<sup>13</sup> Therefore, an improper design of automation could expand problems instead of simplifying the manual control task.<sup>7</sup>

To overcome these issues, a main guideline has been put forward: pilots should always receive feedback from automation about its control strategy.<sup>4,14</sup> These feedback would allow the pilot to be always *in-the-loop*, detect possible errors of automation and respond to them. The feedback should be intuitive and not too invasive for pilots, in order to “keep people well informed, on the top of the issues, but not annoyed and irritated”.<sup>4</sup>

Haptic aids have been proposed as a powerful solution to keep the pilot in-the-loop.<sup>5,14-16</sup> Haptic systems provide tactile feedback that aims to help pilots during the manual control task. In the most common approach, i.e. the Direct Haptic Aid (DHA), the haptic system calculates a control action that would allow the aircraft to perform a certain task, and continuously shows this control action to pilots by means of forces on the stick.<sup>17-19</sup> Pilots are always aware of the DHA control strategy, and can always decide either to be compliant or to override it if they disagree with the system.

Despite the growing interest on the theoretical advantages of haptic aids, there is still some question about their performance compared to automation. Most studies tend to compare haptics with baseline conditions without any external aids. In these cases, haptic aids lead to better performance and reduced control effort.<sup>15,20,21</sup> In a more recent work dealing with car driving, a haptic pedal was compared with full automated system during a curve negotiation task.<sup>22</sup> During the curve negotiation with the automation, the driver could not give input to the car. The haptic aid improved performance compared with the manual control (measured through the peak of lateral error), but it reached lower performance than automation (the peak was larger with haptic aid than with automation). To the best of our knowledge, in literature there are no analogous works regarding typical flight tasks.

The goal of the paper is to compare automation and haptic aids in a compensatory tracking task of an aircraft.<sup>23</sup> A DHA haptic system was designed to help pilots in performing the task. Furthermore, an automated system (AUT) was designed to be “equivalent” to the DHA system, in the sense that it gave the same performance *without pilot in-the-loop*. Since the performance is low, pilots still need to actively control the aircraft. The AUT and DHA systems were tested in an experimental setup *with pilot in-the-loop*. Performance and control activity were evaluated and compared with the manual control task without aids. Furthermore, the open-loop pilot response was estimated to obtain a better insight on the influence of haptics and automation in the pilot control behavior.

Section II presents the compensatory tracking task and a model that describes the overall pilot response in this task. Section III and IV present the design of the haptic aid and the automated system, respectively. In Section V the experiment design is described, and in Section VI results are presented. Finally, conclusions are drawn in Section VII.

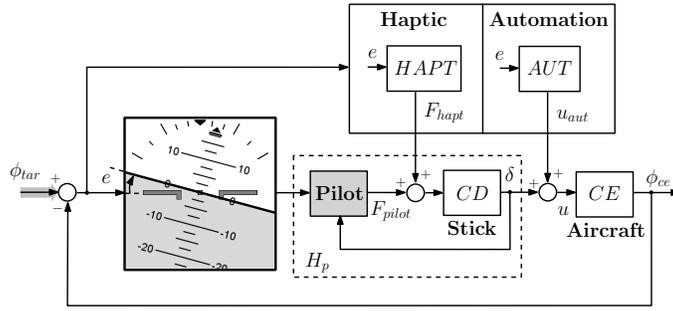


Figure 1. Compensatory tracking task with haptic aid or automation.

## II. Control Task and Identification of Pilot Behavior

This paper focuses on the design of aids for a compensatory tracking task in the roll axis, as depicted in Figure 1. The task consists of tracking a target roll trajectory  $\phi_{tar}$  with the aircraft (i.e., the Controlled Element CE). Only the tracking error  $e$  between the target trajectory and the actual roll angle  $\phi_{ce}$  is shown to the pilot on the compensatory display. The pilot controls the roll dynamics of the aircraft by applying the force  $F_{pilot}$  on the stick (i.e., the Control Device CD). This results in a change of the stick deflection  $\delta$  and consequently in a command signal  $u$  for the aircraft. The haptic aid HAPT or the automation AUT can be used to help pilots during the control task. The haptic aid generates forces  $F_{hapt}$  on the stick, while the automation provides an additional command  $u_{aut}$  directly into the aircraft. Note that, in this model, the pilot can feel the haptic forces through the variations that they cause on the stick deflection  $\delta$ .

The pilot behavior in a compensatory tracking task has been extensively investigated in literature. McRuer provided quantitative models that describe the pilot response to the tracking error for different controlled elements.<sup>23–25</sup> These models assess that pilots adapt their response such that the open-loop transfer function between the tracking error  $e$  and the roll angle of the aircraft  $\phi_{ce}$  resembles an integrator-like dynamics at frequencies around the crossover frequency  $\omega_c$ .<sup>23,24</sup>

$$H_p H_{ce} = \frac{\omega_c e^{-s\tau_s}}{s} \quad (1)$$

Here,  $H_{ce}$  represents the transfer function of CE, while  $H_p$  is the transfer function from the tracking error  $e$  to the stick deflection  $\delta$ . Note that  $H_p$  includes the dynamics of the pilot and the stick, see Figure 1. The parameters  $\omega_c$  and  $\tau_s$  represent the crossover frequency and the pilot visual delay, respectively. However, McRuer's theories did not consider haptic aids or automation in the control loop. The question arises as to whether McRuer's theories are still valid when haptic aids or automation are employed. To answer this question, it is necessary to estimate the open-loop transfer function in tracking tasks with haptic aids or automated systems.

Identification methods that operate in the frequency domain can be used for this purpose.<sup>26,27</sup> These methods require an external signal that excites the system in the frequency range of interest. For this reason, the target trajectory  $\phi_{tar}$  was chosen as a multisine signal:<sup>28</sup>

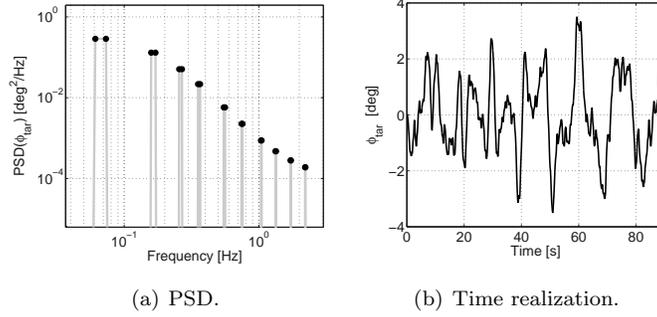
$$\phi_{tar}(t) = \sum_{j=1}^{N_t} T_j \sin(2\pi f_{T_j} t + \psi_{T_j}) \quad (2)$$

where  $T_j$ ,  $f_{T_j}$ , and  $\psi_{T_j}$  are the amplitude, the frequency and the phase of the  $j^{th}$  sinusoidal component of the signal  $x_{tar}$ . Each frequency  $f_{T_j}$  is obtained as an integer multiple of a base frequency  $f_0$ , i.e.  $f_{T_j} = j \cdot f_0$ .

Figure 2 shows the time realization and the Power Spectral Density of the target trajectory used in our paper. The PSD has power on a finite set of frequency points  $\{f_t\}$  in the range  $[0.05 - 3]$  Hz, which is sufficiently large to capture the dynamical properties of pilot response. Furthermore, the time realization of  $\phi_{tar}$  is unpredictable for pilots. More details on  $\phi_{tar}$  are given in Section V.

The estimation of the pilot open-loop transfer function is given by:<sup>26</sup>

$$\hat{H}_{ol}(f) = \frac{\hat{S}_{\phi_{tar}\phi_{ce}}(f)}{\hat{S}_{\phi_{tar}e}(f)}, \quad f \in \{f_t\}. \quad (3)$$



**Figure 2. Target trajectory  $\phi_{tar}$ .**

Here,  $\hat{S}_{vw}$  represents the estimate of the cross-spectra between the generic signals  $v$  and  $w$ , obtained as:

$$\hat{S}_{vw}(f) = \hat{V}(f)W(f) \quad (4)$$

where  $V, W$  are the Discrete Fourier Transform of  $v$  and  $w$ , respectively, and  $\hat{V}$  is the complex conjugate of  $v$ . The coherence functions  $\Gamma^2(\cdot)$  can be used as a reliability indicator of the estimate:

$$\Gamma^2(f) = \frac{|\hat{S}_{\phi_{tar}e}(f)|^2}{\hat{S}_{\phi_{tar}\phi_{tar}}(f)\hat{S}_{ee}(f)}, \quad f \in \{f_t\}. \quad (5)$$

The coherence can assume values between 0.0 and 1.0. The maximum value 1.0 indicates that the measurements of  $e$  and  $\phi_{ce}$  are linearly related and without noise, whereas smaller values indicate the presence of nonlinear distortion and noise.<sup>26</sup>

### III. Design of Haptic Aid

A haptic aid was designed with the aim of helping pilots during the tracking task. The haptic aid was designed according to the Direct Haptic Aid approach(DHA).<sup>29</sup> Based on the tracking error, the haptic aid continuously generates forces on the stick that aim to reduce the roll tracking error. These forces suggests a possible control strategy to pilots, who can decide either to follow or to override them.

The interaction of the pilot with the haptic aid imposes some requirements on the haptic control signal.<sup>30,31</sup> The haptic force should be large enough to be felt by pilots, but at the same time it should leave full authority to pilots to take a different control action. Furthermore, the forces should induce pilots to adopt a force task, i.e. to be compliant with the forces.<sup>31</sup> If this does not happen, the haptic aid may make the control task even more difficult, instead of simplifying it.

A common approach that meets the previous requirements is to mimic the pilot behavior. The haptic forces are designed to be similar to those given by pilots during the tracking task without haptic aids.<sup>20,31</sup> According to Eq. (1), pilot dynamics  $H_p$  change based on the dynamics of the controlled element  $H_{ce}$ . In our experimental setup, the dynamics  $H_{ce}$  was chosen as a double integrator (as detailed in Section V):

$$H_{ce} = \frac{K_{ce}}{s^2} \quad (6)$$

where  $K_{ce}$  represents the gain of the controlled element. The pilot response with these dynamics is given by:<sup>24,32</sup>

$$H_p = K_p(T_L s + 1)e^{-\tau_p s} \quad (7)$$

where  $K_p$ ,  $T_L$ , and  $\tau_p$  are the pilot gain, the lead time constant and the visual time delay, respectively. To obtain similar dynamics as in Eq. (7), the haptic aid was chosen as:

$$H_{hapt}H_{cd} = H_p \quad \Rightarrow \quad H_{hapt} = \frac{K_p(T_L s + 1)e^{-\tau_p s}}{H_{cd}} \quad (8)$$

where  $H_{cd}$  represents the dynamics of the stick. The multiplication of  $H_{hapt}$  with  $H_{cd}$  in Eq. (8) is necessary because the output of the pilot response  $H_p$  is the stick deflection  $\delta$ , while the output of the haptic aid is a force on the control stick.

The values for the parameters in Eq. (8) were chosen according the following criteria. The parameter  $T_L$  approximated the lead time that pilots assume for a double-integrator control. The value for  $T_L$  reported in previous works was 5 s.<sup>23</sup> The visual delay  $\tau_p$  was set to zero, in order to obtain a haptic response slightly faster than the pilot response (typical values for pilots are  $\tau_p = 0.3$  s). The dynamics  $H_{cd}$  were approximated as a static gain, since  $H_{cd}$  behaves like a gain at frequencies around  $\omega_c$  where the model in Eq. (7) is valid (see Section V). The gain  $K_p$  was tuned such that the haptic force could be felt by pilots, but at the same time could leave full authority to pilots. The chosen value was  $K_p = 2$ .

## IV. Design of Automation

The haptic systems are transparent to pilots, in the sense that they show their control strategy by means of forces on the stick. Showing the control action allows to overcome issues like lack of situational awareness, degradation of pilot skills, attention decrement, and over-reliance on automation.<sup>30,33,34</sup> However, the transparency introduces some drawbacks. The haptic forces are first processed by pilots before being fed into the aircraft, resulting in some delay before the haptic control action is actually applied to the aircraft. Furthermore, the interaction of the haptic feedback with the pilot puts some constraints on the forces that can be applied on the stick, as discussed in the previous section. The question arises as to how much these drawbacks influence the performance with respect to an automated system that interface directly to the aircraft.

To address this question, we compared the haptic aid to an “equivalent” automated system AUT. This means that, considering the pilot *out-of-the-loop*, the AUT provided the same control action  $u$  to the aircraft as the haptic system. The system regulated the tracking error to zero with the same performance as the haptic system. With this mind, the AUT was obtained as:

$$H_{aut} = H_{hapt}H_{cd} = K_p(T_L s + 1) \quad (9)$$

The haptic aid and AUT provide low performance with the pilot out-of-the-loop. Thus, the pilot control action is still needed to perform the task.

A further analysis is required to investigate how the tracking task with automation is seen from the pilot’s point of view. The pilot is not aware of the control command from the automation, since it is provided directly to the aircraft. Furthermore, the effect of the automation on the aircraft roll angle can not be deduced from the compensatory display, since the display does not show the roll angle but only the tracking error. Thus, the automated system is obscured from the pilot. Figure 3 shows the control loop in Figure 1 rearranged in the case when the automation is employed. The control task with the automated system results equivalent to a control task where:

- the target trajectory  $\phi_{tar}$  is prefiltered with the filter  $H_{tar}$

$$H_{tar} = \frac{1}{1 + H_{ce}H_{aut}} \quad (10)$$

- the aircraft has a modified dynamics  $H_{ce-aut}$ :

$$H_{ce-aut} = \frac{H_{ce}}{1 + H_{ce}H_{aut}} \quad (11)$$

Figure 4(a) and Figure 4(b) show the magnitude of  $H_{tar}$  and  $H_{ce-aut}$ , respectively. The magnitude of  $H_{tar}$  is lower than 1 at low frequencies, whereas it becomes slightly larger at frequencies around 1.5 Hz. Thus, the filter  $H_{tar}$  reduces the power of  $\phi_{tar}$  at low frequencies. Since most of the power of  $\phi_{tar}$  is concentrated at low frequencies (see Figure 2), the filtered trajectory becomes less demanding for pilots. The modified dynamics  $H_{ce-aut}$  is stable and behaves like a gain at low frequencies. The control of these dynamics is much easier compared to the double integrator. Thus, from the pilot point of view, the use of automation in the compensatory task drastically reduces the complexity of the task.

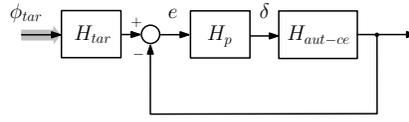


Figure 3. Compensatory tracking task rearranged for the case when automation is employed.

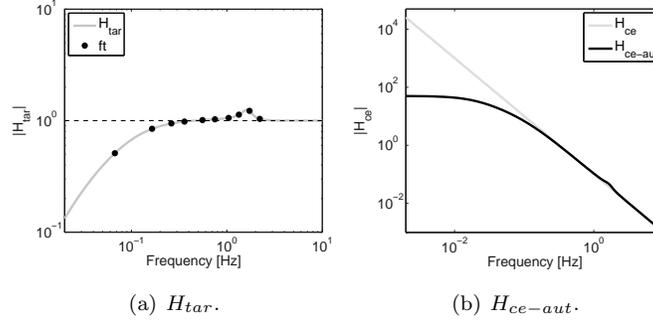


Figure 4. Prefilter  $H_{tar}$  and equivalent dynamics  $H_{ce-aut}$  for the tracking task with automation.

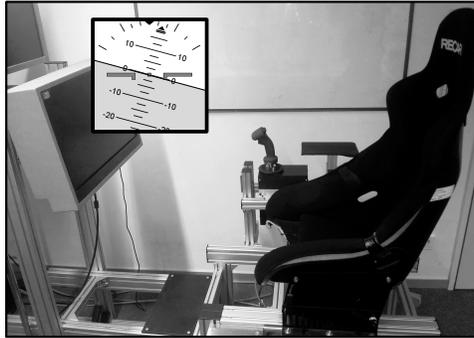


Figure 5. Test station with high-resolution display and haptic sidestick.

## V. Experiment Setup

To compare haptics and automation from a quantitative point of view, a human-in-the-loop experiment was performed that resembled control of an aircraft during a tracking task. In this section, the details of the experimental design are described.

### Task and Apparatus

The experimental task involved the tracking of a target trajectory of a roll angle. As illustrated in Figure 5, the tracking error  $e$  was presented on a high-resolution display from VPixx Technologies Inc., Canada. The resolution of the display is 1920(H) x 1200(V) pixels, the refresh rate is 120 Hz. The error  $e$  was shown as the angular difference between the moving horizontal line and the fixed aircraft symbol. The vertical offset between the horizontal line and the aircraft symbol, which indicates the pitch angle of the aircraft, was kept to zero. The refresh rate of the display was 120 Hz.

Participants controlled the roll angle of the aircraft with a control-loading sidestick from Wittenstein Aerospace & Simulation GmbH, Germany. The dynamics of the sidestick resembled a mass-spring-damper system, where the mass, the damping, and the stiffness can be set with different values. The stiffness of the stick was set to 1.1 N/deg in accordance with previous works dealing with similar control tasks.<sup>32,35</sup> The mass and the damping were set to the minimum available values. The resulting sidestick dynamics were:

$$H_{cd} = \frac{1}{0.0151 s^2 + 0.0616 s + 1.1} \quad [deg/N] \quad (12)$$

Since the pitch axis of the sidestick was not used during the experiment, it was fixed in the zero position. An armrest was positioned close to the sidestick.

The aircraft roll attitude dynamics was chosen as:

$$H_{ce} = \frac{4}{s^2} \quad [deg/deg] \quad (13)$$

The double integrator resembles the dynamics of a simplified roll attitude control of an aircraft.<sup>36</sup> The gain of  $H_{ce}$  was chosen to give optimal control authority on the roll angle.<sup>32</sup>

A real-time computer running xPC Target (MathWorks, Inc.) was used to interface the primary flight display and the sidestick with the simulated aircraft dynamics. The update frequency of the real-time computer was 500 Hz.

## Target Trajectory

The target trajectory  $\phi_{tar}$  was selected as the multisine signal in Eq. (2). The amplitudes  $T_j$  were distributed according to the absolute value of a filter  $H_T$ :<sup>28</sup>

$$H_T(j\omega) = \frac{(T_1 j\omega + 1)^2}{(T_2 j\omega + 2)^2} \quad (14)$$

where  $T_1 = 0.1$  s and  $T_2 = 0.8$  s. To generate an integer number of periods in the measurement time, the base frequency  $f_0$  was chosen as the inverse of the measurement time  $T = 81.92$  s. The frequencies  $f_{T_j}$  were logarithmically spaced multiples of the base frequency  $f_0$ . The phases  $\psi_{T_j}$  were selected from a random set to yield an approximately Gaussian distribution of the values of  $\phi_{tar}$ .<sup>28</sup> The resulting time realization was scaled to give a power of 2 deg<sup>2</sup>.

## Participants and Experiment Procedure

Six male participants between the age of 25 and 32 years were recruited for the experiment. All participants were affiliated to Max Planck Institute for Biological Cybernetics, three of them had previous experience with compensatory control tasks.

Before starting the experiment, participants were instructed to minimize the error shown in the compensatory display. They were informed about the possible presence of haptic forces on the control device, but no specific instructions were given on how to exploit the haptic force. All participants performed three tracking conditions: tracking task without aids (NoAID), with haptic aid (HAPT), and with automated system (AUT). The order of the conditions was randomized between participants according to a Latin Square Matrix. For each condition, participants performed some training trials until they reached a consistent level of performance. Then, four more trials were performed to collect the measurement data. Each trial lasted 90 s, with regular breaks in between the trials. The whole experiment lasted around three hours, split in two different sessions of 1.5 hours.

## Data Collection and Analysis

The time realizations of several signals were logged at 100 Hz during the experiment. These included the aircraft roll angle  $\phi$ , the human force  $F_{hum}$ , and the deflection of the stick  $\delta$ . Only the last T seconds of the measurements were considered for the data analysis. The time interval T was chosen as 81.92 s, which is a integer multiple of the period of  $x_{tar}$ . This allowed to remove transients at the beginning of the trials and to avoid the leakage bias in the estimation of pilot response.<sup>26</sup>

Several measures were calculated to investigate the influence of haptics and automation on the pilot performance and control behavior. The pilot performances in the three tracking conditions were evaluated from the variance of the tracking error  $\sigma^2(e)$ :

$$\sigma^2(e) = \frac{\sum_{k=1}^N (e(k) - \bar{e})^2}{N} \quad (15)$$

where N indicates the number of time samples and  $\bar{e}$  the mean value of  $e$ . The variances of the stick deflection  $\delta$  and of the human force  $F_{pilot}$  were calculated as measures of the pilot control activity and the force needed

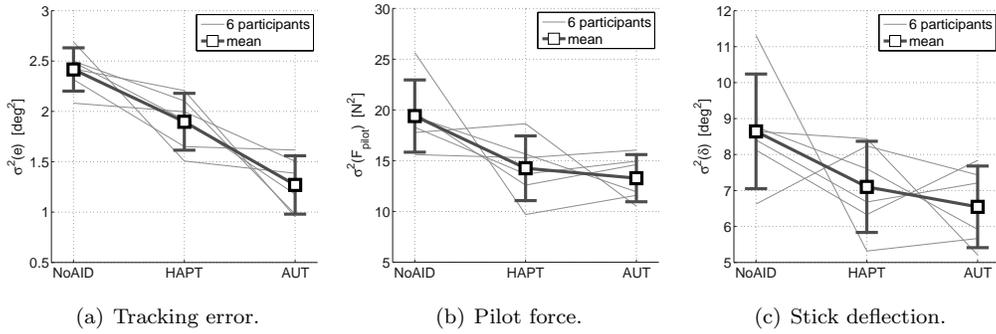


Figure 6. Mean and 95 % confidence intervals of  $\sigma^2(\cdot)$  over all participants.

Table 1. Results of post-hoc tests with Bonferroni correction for  $\sigma^2(\cdot)$  data.

Independent variables	Dependent measures					
	$\sigma^2(e)$		$\sigma^2(F_{pilot})$		$\sigma^2(\delta)$	
Factor	p	Sig. <sup>a</sup>	p	Sig.	p	Sig.
NoAID vs. HAPT	0.067	*	0.098	*	0.582	–
NoAID vs. AUT	0.003	**	0.078	*	0.239	–
HAPT vs. AUT	0.086	*	1.000	–	1.000	–

a. \*\* : highly significant ( $p < 0.050$ ) \* : marginally significant ( $0.050 \leq p < 0.100$ )  
 – : not significant ( $p \geq 0.100$ )

to perform the task, respectively. To test statistical differences between the variances in the three tracking conditions, a one-way repeated measurement analysis of variance (ANOVA) was used. Post-hoc tests with Bonferroni correction were employed to perform pairwise comparisons between the tracking conditions.

Non-parametric estimates of pilot open-loop frequency response functions were calculated using Eq. (3). To reduce the variance of the estimates, the time signals were averaged over the four trials and the resulting estimates over two adjacent frequency points.<sup>37</sup> The reliability of the estimates was evaluated through the coherence function in Eq. (5). Then, the crossover frequency  $f_c$  and the neuromuscular peak of the open-loop responses were calculated and statistically compared with ANOVA and post-hoc tests with Bonferroni correction. The crossover frequency  $f_c$  represents the bandwidth of the pilot response. High values of  $f_c$  imply a fast dynamic response and a higher ability to follow the tracking signal. On the other hand, high neuromuscular peaks should be avoided, since they can induce unstable oscillations on the aircraft.<sup>38</sup>

## VI. Results and Discussion

This section presents the results of the experimental comparison between haptics and automation. Pilot performance and control activity are contrasted between the experimental tracking conditions. Furthermore, differences in the pilot response are investigated.

### A. Performance and control activity

Pilot performance were evaluated using the variances of the tracking error  $\sigma^2(e)$ . Figure 6(a) shows the results from each participant (thin lines), together with the mean and the 95 % confidence interval (error bars). Results of ANOVA ( $F(2,10) = 10.627$ ,  $p < 0.05$ ) and post-hoc tests with Bonferroni correction (Table 1) indicated that all the differences between conditions were statistically significant. Performance improved with haptic and automation compared with the baseline condition without aids. However, the haptic did not achieve the same performance as the automation, which reduced  $\sigma^2(e)$  compared to NoHA with almost 50%.

Variances of pilot force  $F_{pilot}$  and stick deflection  $\delta$  were calculated as measures of the pilot effort. Figure 6(b) and Figure 6(c) depict the means and the 95 % confidence interval of  $\sigma^2(F_{pilot})$  and  $\sigma^2(\delta)$ ,

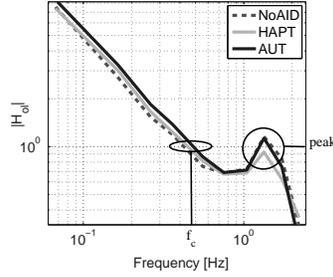


Figure 7. Estimates of  $H_{ol}$  for participant 4.

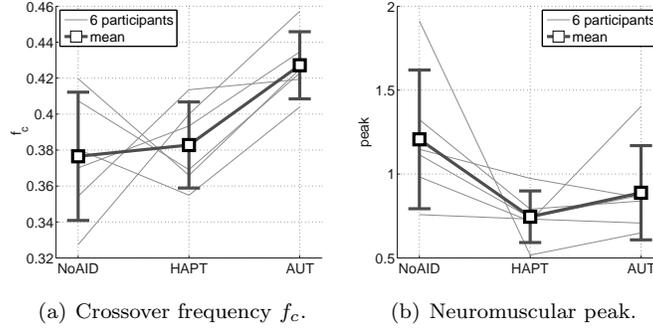


Figure 8. Mean and 95 % confidence intervals of  $f_c$  and neuromuscular peak over all participants.

respectively. The pilot force was affected by the external aids ( $F(2,10) = 5.064$ ,  $p < 0.05$ ). Post-hoc test with Bonferroni correction revealed a statistically significant difference between NoAID and the other two tracking conditions (Table 1). This indicates that the haptic aid allowed the pilot to significantly reduce the forces needed to control the aircraft. Furthermore, the forces applied with HAPT and AUT were found to be similar. The variance of the stick deflection was slightly lower for AUT and HAPT conditions compared with NoAID. However, no statistically significant difference was found between the three conditions ( $F(2,10) = 2.876$ ,  $p = 0.103$ ).

As discussed in Section IV, the tracking task with the automation is equivalent to a tracking task with a different and easier to control aircraft dynamics  $H_{ce-aut}$ . The lower performance in the HAPT condition compared to the AUT condition indicates that participants found easier to control  $H_{ce-aut}$  rather than the double integrator  $H_{ce}$  combined with the haptic forces. However, the variances of pilot control forces were similar between HAPT and AUT conditions. This indicates that the haptic forces allowed participants to control the double integrator with the same amount of control effort needed for the easier dynamics.

## B. Pilot response

An analysis was made to look for the influence of haptic and automation on the pilot open-loop responses. Figure 7 shows the open-loop responses of participant 4. High coherence values indicated reliability of the estimates ( $\Gamma^2(f) > 0.8$  for all  $f \in \{f_i\}$ ). These responses are representative for all participants. All the estimates closely follow an integrator-like dynamics at frequencies close to the crossover frequencies  $f_c$  where  $|H_{ol}(f_c)| = 1$ . Thus, participants adapted their responses to the tracking error to yield an open-loop transfer function in line with McRuer theories.<sup>36</sup> This highlights that McRuer theories can still be applied when haptics or automation are employed in the control loop. The peak in the responses at high frequencies was related to the neuromuscular system of the pilot's arm,<sup>36</sup> see Figure 7.

The crossover frequency was found to be influenced by the presence of external aids ( $F(2,10) = 5.122$ ,  $p = 0.029$ ), see Figure 8(a). Post-hoc tests with Bonferroni correction revealed that AUT was statistically different from the other two conditions. This is in complete agreement with the higher performance found for the AUT system. The values of the neuromuscular peaks decreased with HAPT, as depicted in Figure 8(b). Although the ANOVA test revealed a marginally significant effect ( $F(2,10) = 3.198$ ,  $p = 0.084$ ), post-hoc

**Table 2. Results of post-hoc tests with Bonferroni correction for  $\sigma^2(\cdot)$  data.**

Independent variables	Dependent measures			
	$f_c$		Peak	
Factor	p	Sig. <sup>b</sup>	p	Sig.
NoAID vs. HAPT	1.000	–	0.207	–
NoAID vs. AUT	0.131	–	0.659	–
HAPT vs. AUT	0.008	**	0.807	–

b. \*\* : highly significant ( $p < 0.050$ ) \* : marginally significant ( $0.050 \leq p < 0.100$ )  
 – : not significant ( $p \geq 0.100$ )

tests for pairwise comparisons did not result in statistically significant differences between the conditions due to the large variance on NoAID and AUT conditions.

## VII. Conclusions

To investigate the effects of haptics and automation on pilot performance and control behavior, two equivalent haptic and automated system were tested in a compensatory tracking task and compared with a baseline condition without external aids. Participants significantly improved their performance with the haptic aid and the automation. In particular, the automation outperformed the other two conditions. The control effort decreased with both external aids. This was indicated by the lower forces applied by pilots to perform the tracking task. Furthermore, participants modified their open-loop responses in different ways between the three tracking conditions. The automation lead to an increased crossover frequency, whereas the haptic system reduced the peak of the neuromuscular system.

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