~~Transforming Civil Helicopters into Personal Aerial Vehicles: Modeling, Control and Human-in-the-loop Validation~~

Transforming Civil Helicopters into Personal Aerial Vehicles: Modeling, Control and Validation

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This paper presents the implementation of robust control strategies to augment an identified state-space model of a civil light helicopter. The aim of this study is to augment the helicopter model to achieve response types and handling qualities of a new category of aircraft called Personal Aerial Vehicles (PAVs), which can be flown even by inexperienced pilots. Two control methods are considered to augment the helicopter model, H∞ and μ-synthesis. Differences, advantages and limitations of the implemented control architectures are highlighted with respect to the selected PAV reference dynamics in terms of robust stability, nominal performance and handling qualities. Furthermore, results are presented of an experiment performed with the Max Planck Institute CyberMotion Simulator. The aim of the experiment was to assess the discrepancies between the two augmented systems and the PAV reference model. The experiment consists of piloted closed-loop control tasks performed by participants without any prior flight experience. The results show that the two implemented augmented systems allow inexperienced pilots to achieve workload and performance levels comparable to those defined for PAVs.

Nomenclature

$ACAH$	=	Attitude Command Attitude Hold
CMS	=	CyberMotion Simulator
HQs	=	Handling Qualities
MTE	=	Mission Task Element
$PATS$	=	Personal Aerial Transportation System
$PAVs$	=	Personal Aerial Vehicles
$RCAH$	=	Rate Command Attitude Hold
TRC	=	Translational Rate Command
$\delta_{lat}, \delta_{lon}, \delta_{ped}, \delta_{col}$	=	helicopter control inputs (lateral cyclic, longitudinal cyclic, pedals rudder, collective lever), $[deg]$
u, v, w	=	velocity components along the body axes (longitudinal, lateral,
p, q, r	=	fuselage angular rates (roll rate, pitch rate, yaw rate), $[rad/s]$ vertical), $[m/s]$
a_x, a_y, a_z	=	accelerometer components along the body axes (longitudinal, lateral,
ϕ, θ, ψ	=	fuselage angular attitude (roll, pitch, yaw) Earth-fixed coordinates, $[rad]$ vertical), $[m/s^2]$

I. Introduction

In the past few decades, congestion issues have been increasingly affecting the road network of many cities all over the world [1]. The myCopter project (2011-2014, funded by the European Commission under the 7th Framework) investigated new concepts and technologies that could alleviate the congestion situation [2]. Specifically, myCopter investigated the enabling technologies required to create a new transportation system, the so-called Personal Aerial Transport System (PATS) that would combine the best of ground- and air-based transportation features. Within the project, it was acknowledged that a key element of a PATS would be the Personal Aerial Vehicle (PAV), a flying vehicle that would be used by the traveling public. Designing new vehicle prototypes was not part of the project's goal. However, it was considered important to investigate response types and

Handling Qualities (HQs) that could reduce the amount of training necessary to learn how to fly a PAV to that required to learn how to drive a car [3]. These response types were tuned to ensure Level 1 HQs according to the Aeronautical Design Standard-33 requirements (ADS-33E-PRF) [3]. After the end of the project in 2014, these results inspired further studies aiming at investigating whether augmentation strategies can be applied to actual vehicles, such as helicopters, in order to achieve HQs defined for PAVs.

The research presented in this paper proposes civil light helicopters as possible candidates for PAVs. This choice is motivated by the fact that civil light helicopters possess many properties a PAV should have (e.g. size, weight, number of seats, vertical take-off and landing capabilities). Nevertheless, several concerns can be raised, questioning whether civil light helicopters can indeed be transformed into PAVs. Civil helicopters are currently still a niche product and learning how to fly them requires considerable time and dedication. Furthermore, helicopters are generally characterized by complex dynamics that make them difficult to model and control. Therefore, civil light helicopters are still far from being considered broadly accessible to the general public, which is a main feature that PAVs should possess.

A crucial step towards the transformation of civil light helicopters into PAVs is the design of control augmentation systems that can make currently existing helicopters easier to fly, for both experienced and inexperienced pilots. In the last few decades many studies on control augmentation have been conducted to enhance helicopters stability and controllability and to meet demanding specifications like the HQs requirements of the ADS-33E-PRF [4, 5].

However, most control studies on helicopters have been conducted for military purposes. Therefore, studies for improving helicopters HQs have been mostly focused on highly trained experienced pilots. The recent definition of PAVs handling qualities and response types provided by the myCopter project [3] extended for the first time these concepts to inexperienced pilots.

The goal of this paper is to ~~demonstrate that~~ *prove whether* augmented control strategies can be applied to transform civil light helicopters' HQs and response types into those defined for PAVs [3], therefore making helicopters easy to fly for inexperienced pilots. To achieve this goal, two control methods are considered here: H∞ and μ-synthesis. ~~In a previous study [6], these control strategies~~

~~were designed and applied to an identified model of a Robinson R44 Raven II in hover.~~ *The two control strategies are designed and applied to an identified model of a Robinson R44 Raven II in hover [7].*

~~The two control strategies were then compared with each other and with respect to the PAV reference model in terms of stability and performance.~~

In a previous study [6], the two control strategies had been applied on an initial identified model of the same helicopter. Since the previous study [6], an improved model of the Robinson R44 has been identified through an iterative validation process, performed with the help of a helicopter pilot and the use of the Max Planck Institute (MPI) CyberMotion Simulator [7].

~~For this reason, the two control methods have been applied again on the newly identified model and slightly different results have been obtained with respect to those shown in [6]. These new results are presented in this paper and analyses are performed to highlight discrepancies between the augmented systems and the PAV reference model in terms of response types and HQs.~~

The results obtained by applying the two control strategies on the newly identified model are shown in this paper. The augmented systems are compared in terms of robustness and performance to assess their capability of achieving PAVs responses and HQs. From the analysis, some discrepancies are highlighted between the augmented systems and the PAV model.

~~Results of an experiment conducted to further validate the two control systems are also presented here.~~

The magnitude of these discrepancies is assessed in the second part of the paper with a human-in-the-loop experiment. The assessment is done in terms of objective and subjective performance and workload.

In the experiment, participants without any prior flight experience ~~were~~ *are* invited to perform piloted closed-loop control tasks in a simulated environment with the use of the MPI CyberMotion Simulator. ~~The experiment shed light on differences, capabilities and limitations of the implemented control systems.~~ *The results of the experiment shed light on differences, advantages and limitations of the two augmented systems. Therefore, the magnitude of the discrepancies shown in the previous analysis is evaluated. Furthermore, the feasibility of an actual implementation on a real civil light* *helicopter is discussed.*

~~The paper is divided into two main parts. The first part describes the two control designs. First, features of the identified helicopter model are highlighted that are important for control design purposes. Then, a description is given of the design methods used for implementing the H∞ and the μ-synthesis control techniques. The obtained results are described in terms of stability and performance. A discussion presents differences, advantages and limitations of the implemented control architectures with respect to the considered requirements.~~

~~In the second part of the paper, the experiment is presented. First, the experimental method and the implemented setup are described in details. Then, the obtained results are shown with a final discussion. Conclusions and recommendation are given at the end of the paper.~~ *Conclusions and recommendation are given at the end of the paper to answer the main research question asked in this work as to whether civil light helicopters can be considered as possible candidates for future PAVs.*

II. Helicopter model and robust control

The augmentation strategies ~~implemented~~ *described* in this paper are applied to an identified helicopter model, obtained from the data collected during two hours of flight tests with a Robinson R44 Raven II helicopter. The flight tests focused on the hover trim condition. The identification procedure that was used to obtain the final model can be found in [8]. The final model is a fully coupled 12 Degrees Of Freedom (DOF) state-space model valid within the frequency range of 0.1-16 rad/sec. Furthermore, the model is linear and can be expressed in the classical form:

$$\begin{aligned}\dot{\mathbf{x}} &= \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \\ \mathbf{y} &= \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u}\end{aligned} \tag{1}$$

where the inputs are the four pilot controls

$$\mathbf{u} = [\delta_{lat}, \delta_{lon}, \delta_{ped}, \delta_{col}] \tag{2}$$

the outputs are the helicopter response signals measured during the data collection

$$\mathbf{y} = [u, v, w, p, q, r, a_x, a_y, a_z, \phi, \theta] \tag{3}$$

and the state vector $\mathbf{x}$ is composed of 20 states that represent the rotor-body dynamics [7].

The capability of accounting for rotor/flap body coupling dynamics, lead-lag dynamics and coning-inflow dynamics is a very important feature of this model. It is well known that these dynamics can limit control feedback gains on attitude and rates [9, 10]. Therefore, this model is well suited for implementing reliable control augmentation systems.

Control system designs have to account for as many physical characteristics as possible to ensure good results, especially when applied to complex dynamics like helicopters. The identified helicopter model considered here is unstable, non-minimum phase and presents important rotor-body coupling dynamics. Many successful implementations can be found in literature of ~~robust controllers~~ *H∞ control methods [13]* applied to helicopter models with similar characteristics [4, 11, 12]. ~~For this reason, two robust control strategies were chosen to solve the control problem considered in this paper. In particular, the H∞ and the μ-synthesis control approaches were selected.~~

~~The H∞ control is a robust approach that allows for stability and performance to be satisfied against external disturbances and noise, while minimizing the control energy action [13].~~

~~Furthermore, it~~ *The H∞ control method* is a Multi-Input Multi-Output (MIMO) approach and it is frequency based. Since the identified helicopter model is a MIMO system and the PAV HQs are frequency based, the H∞ approach was assessed well-suited to solve the control problem considered here *and achieve the goal proposed in the paper.*

However, the H∞ control method does not ensure stability and performance *to be achieved* with respect to model parametric uncertainties. *This limitation was observed during the controller implementation as will be shown in the following of the paper.* ~~Conversely~~ *Therefore*, the μ-synthesis *control method was considered, since it is able ensure robustness* ~~can do this~~ by directly including the *model* parametric uncertainties into the optimization problem [14]. ~~Since these uncertainties were part of the identified helicopter model [8], the μ-synthesis control technique was also implemented to allow for robust stability and performance to be achieved.~~ ~~Usually~~ *Unfortunately*, a disadvantage of the μ-synthesis method is to provide controllers with high orders, whose reduction while maintaining robustness and required performance is not a trivial task. Low order controllers are preferable since they are easier to implement, have higher reliability and are computationally less demanding.

Another disadvantage is that lower performance levels are generally reached with respect to the H∞ control method in order to ensure robust stability. ~~For these reasons, an order reduction method was also considered to reduce the complexity of the two implemented controllers.~~ *To highlight advantages and limitations of the two control approaches, both control methods were considered and compared against each other.*

III. Control design

Both H∞ and μ-synthesis control methods consist of solving an optimization problem:

- in the H∞ control technique, the H∞ norm of the closed-loop response from the exogenous inputs to the controlled outputs is minimized;
- in the μ-synthesis control technique, the structured singular value is minimized.

Two main steps are necessary to solve these problems. The first step consists of designing a control scheme and of selecting the weighting functions associated with the quantities to minimize. The second step consists of implementing a controller to stabilize the system and minimize the weighted quantities.

The control scheme in Fig. 1 was considered for implementing both control methods. The *Helicopter Model [P]* block in the middle represents the identified linear state-space model in hover trim condition.

In this work, a realistic flight scenario was considered that could take into account disturbances, noise and model uncertainties. Therefore, both control methods were designed to ensure stability and performance specifications against disturbances (*Disturbances* $[W_{dist}]$) and noise (*Sensors Noise* $[W_n]$) acting on the system. The μ-synthesis control technique was implemented to ensure such specifications also against model uncertainties (*Uncertainties* $[\Delta]$).

The *Uncertainties* $[\Delta]$ block was designed to contain the parametric uncertainties of the helicopter model that are due to discrepancies between the identified model and the actual helicopter dynamics. The *Disturbances* were considered as real atmospheric turbulences that might be experienced in hover and low speed flight regime. ~~To do this, the *Turbulence Model* $[W_{dist}]$ block was~~

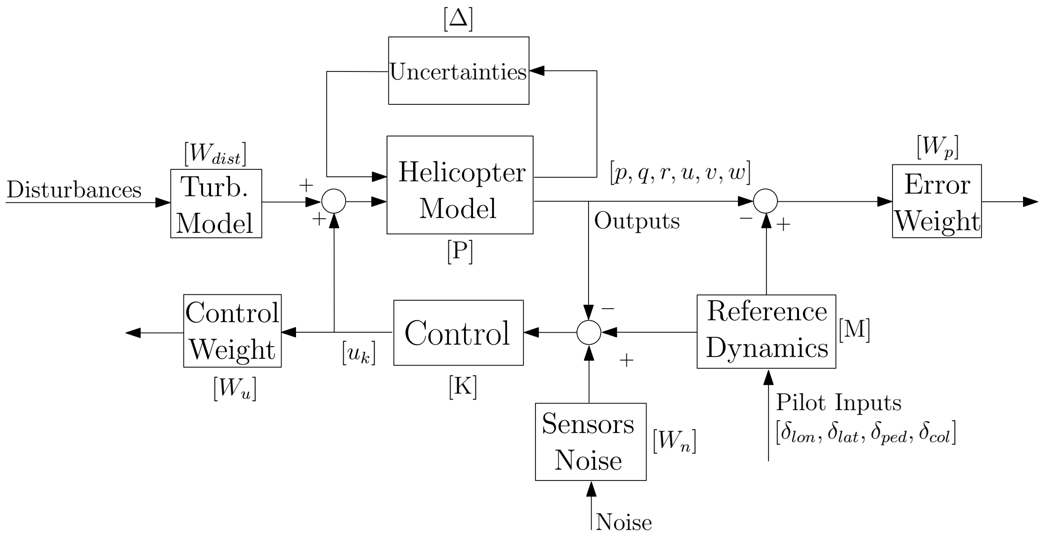


Fig. 1: Control system architecture

~~designed by using the Control Equivalent Turbulence Input (CETI) method [15].~~ *No data were collected to identify a specific turbulence model for the R44 helicopter. Therefore, the turbulence model developed by the German Aerospace Center DLR for the EC135 helicopter [15] was used here. This model was designed with the Control Equivalent Turbulence Input (CETI) method [15] and is valid for hover and low speed flight conditions. In Fig. 1 the Turbulence Model [W_{dist}] block is composed of four transfer functions driven by a white noise (Disturbances).* ~~Finally,~~ The *Sensors Noise* [W_n] block was designed with noise shaping functions based on realistic accelerometers and rate-gyros. Details about these blocks are provided in [6] and are not described here for sake of brevity.

The external inputs of the system were considered as *Pilot Inputs* [$\delta_{lon}, \delta_{lat}, \delta_{ped}, \delta_{col}$], external *Disturbances* [W_{dist}] and sensors *Noise* [W_n].

In order to achieve response types and HQs associated with the PAV dynamics, a model following approach was implemented. The *Reference Dynamics* [M] that the augmented systems had to follow were those defined during the myCopter project. These include Translational Rate Command (TRC) response types in lateral, longitudinal and vertical translational degrees of freedom, and a Rate Command Attitude Hold (RCAH) response type in the yaw axis. The yaw axis response type was defined to ensure Level 1 HQs, which corresponds to desirable flying qualities according to the

ADS-33-PRF [16]. The transfer functions associated to these responses are listed below:

$$\begin{aligned} M_{lon} &= \frac{u_{ref}}{\delta_{lon}} = -\frac{1.05}{1.25s+1} \\ M_{lat} &= \frac{v_{ref}}{\delta_{lat}} = \frac{1.05}{1.25s+1} \\ M_{yaw} &= \frac{r_{ref}}{\delta_{ped}} = \frac{0.03e^{-0.008}}{0.25s+1} \\ M_{vert} &= \frac{w_{ref}}{\delta_{col}} = \frac{e^{-0.20}}{5s+1} \end{aligned} \tag{4}$$

Two more transfer function responses defined in the myCopter project were taken into consideration as reference for pitch and roll dynamics (Eq. (5)).

$$\begin{aligned} M_{pitch} &= \frac{\theta_{ref}}{\delta_{lon}} = \frac{0.36e^{-0.008}}{s^2+4.22s+5.49} \\ M_{roll} &= \frac{\phi_{ref}}{\delta_{lat}} = \frac{0.73e^{-0.008}}{s^2+3.51s+5.49} \end{aligned} \tag{5}$$

These correspond to Attitude Command Attitude Hold (ACAH) response types with associated Level 1 HQs.

After defining the control scheme architecture, the second step was performed, consisting of solving the two optimization problems (H∞ and μ-synthesis) to obtain the corresponding controllers ([K] in Fig. 1). Both optimization problems had to ensure the minimization of the weighted variables, i.e. the control action u_k weighted through the weighting function W_u, and the difference between the outputs of the reference dynamics and those of the helicopter $[u, v, w, p, q, r]$ weighted with the weighting function W_p. This, while ensuring robust stability against uncertainties, external disturbances and sensor noise. Therefore, the 6 inputs ~~of~~ *to* the controllers [K] were selected as the difference between the *Reference Dynamics* and the helicopter *Outputs* (Fig. 1). The 4 outputs of the controllers were chosen as the control action $[u_k]$ applied to the helicopter model.

The weighting functions were chosen as high pass filters for the control function (W_u) and low-pass filters for the performance function (W_p), as generally done in literature [17]. The bandwidth of the control function (W_u) was selected by ~~tacking~~ *taking* into consideration the maximum velocity achievable by realistic helicopter's actuators ~~(Eq. (7))~~. The bandwidth of the performance function (W_p) was selected to ensure a good model following within the frequency range of interest ~~(Eq. (8))~~.

However, the choice of the weighting functions gains was not trivial as a good tracking of ~~all~~ *the entire* PAV's reference dynamics (Eqs. (4), (5)) was hard to achieve. ~~This problem was related~~

~~to the nature of the PAV model, defined as a generic decoupled linear helicopter dynamics with a transfer function representation of the rotational dynamics. As such,~~ *The PAV model is defined as a linear model in which rotational and translational dynamics are decoupled from each other [24].* Therefore, ACAH and TRC response types of the PAV model were separately ~~defined~~ *tuned* and no coupling was included between the two. However, helicopters' translational dynamics are ~~strictly~~ *strongly* coupled to the rotational dynamics. For this reason, achieving a good ~~tracking~~ *matching* of both translational and rotational PAV's responses was not possible.

Furthermore, increasing the control action by limiting the gains of W_u did not provide any improvement as neither of the two optimization problems (H∞ and μ-synthesis) could find stable solutions. This was attributed to the lead-lag dynamics included in the identified helicopter model. As reported in literature, lead-lag dynamics can limit control feedback gains on the angular rates [9, 10].

To overcome these issues a trade-off was necessary that could ensure a good model following of both translational and rotational dynamics. Therefore, an optimization problem was defined. This was done for the H∞ control technique only as it was computationally harder to find optimal weights for the μ-synthesis control technique. Three objective functions were considered to solve the optimal problem.

The first objective function was selected as the solution (γ) of the H∞ control problem. Such solution represents the H∞ cost function for which it holds that $||CL||_\infty < \gamma$, where CL is the closed loop system architecture of Fig. 1. This first objective function was selected to allow for stable solutions to be selected. It is important to notice that the first objective function alone cannot allow the selection of the weighting functions gains as the optimization would choose gains equal to zero to minimize γ. For this reason, two more objective functions were selected that had no dependency on the weighting functions. The selection was done to ensure both translational and rotational PAV's responses to be followed.

The second objective function was selected to ensure a good tracking of the PAV translational responses (TRC response types). This objective function was obtained by first computing the differences between the frequency responses of the translational velocities of the augmented system (obtained from the H∞ problem solved for the current set of weighting functions' gains) and those of the PAV reference model. Such differences were computed in terms of magnitude and phase:

$$J_i = \sum_{\omega_1}^{\omega_{n_\omega}} \left[(|T_{aug_i}| - |T_{ref_i}|)^2 + (\angle T_{aug_i} - \angle T_{ref_i})^2 \right] \tag{6}$$

with i going from 1 to 3, T_{aug_i} representing the i-th translational response of the augmented system, and T_{ref_i} the i-th translational response of the PAV reference model. The number of frequencies was set to 20 and the frequency range was specified between $\omega_1 = 0.3$ rad/sec and $\omega_{n_\omega} = 16$ rad/sec. The objective function was then computed as the average value of the three cost functions J_i obtained from Eq. (6).

The third objective function was selected to ensure a good tracking of the PAV rotational responses (ACAH response types). This objective function was defined as the second objective function but with the errors in Eq. (6) computed with respect to the three ~~rotational velocities~~ *rotational rates*.

The optimization problem resulting from choosing these three objective functions represents a multi-objective problem with competing objectives (the second and the third objectives compete with each other and with the first objective). To solve this problem, a multi-objective genetic algorithm was implemented. Genetic algorithms provide a set of solutions called Pareto front [18]. Among these solutions, those were eliminated with $\gamma > 1$ to ensure stable solutions and good disturbance rejection to be achieved. Then, the optimal solution was selected as the one corresponding to the minimum averaged value between the second and the third objective functions.

The resulting weighting functions obtained from the optimization problem are reported in Eqs. 7 and 8.

$$\begin{aligned} W_u =& diag\left[W_{u_{lat}}, W_{u_{lon}}, W_{u_{ped}}, W_{u_{col}}\right] \\ =& diag\left[0.0283, 0.0635, 0.0010, 0.0225\right] \frac{0.05s+1}{0.005s+1} \end{aligned} \tag{7}$$

$$\begin{aligned} W_p =& diag\left[W_{p_p}, W_{p_q}, W_{p_r}, W_{p_u}, W_{p_v}, W_{p_w}\right] = diag\Big[9.0010, 9.7547, \\ & 6.1185, 1.0469, 1.0586, 5.7131\Big] \frac{0.005s+1}{0.05s+1} \end{aligned} \tag{8}$$

It is interesting to notice that the performance gains associated with the roll [W_{p_p}] and the pitch axes [W_{p_q}] have similar values and are approximately nine times larger than the longitudinal [W_{p_u}] and the lateral [W_{p_v}] gains, respectively.

The weighting functions in Eqs. 7 and 8 were used to solve both H∞ and μ-synthesis control problems. The H∞ problem provided a controller with order 61 while the μ-synthesis provided a controller with order 105. *As expected, the μ-synthesis approach produced a significantly more complex controller than the H∞ approach. This must be taken into account if an implementation of the designed controllers on real control hardware is considered. Although an order reduction method can be employed to solve this problem, a similar reduction of complexity is expected to be obtained on both H∞ and μ-synthesis controllers.*

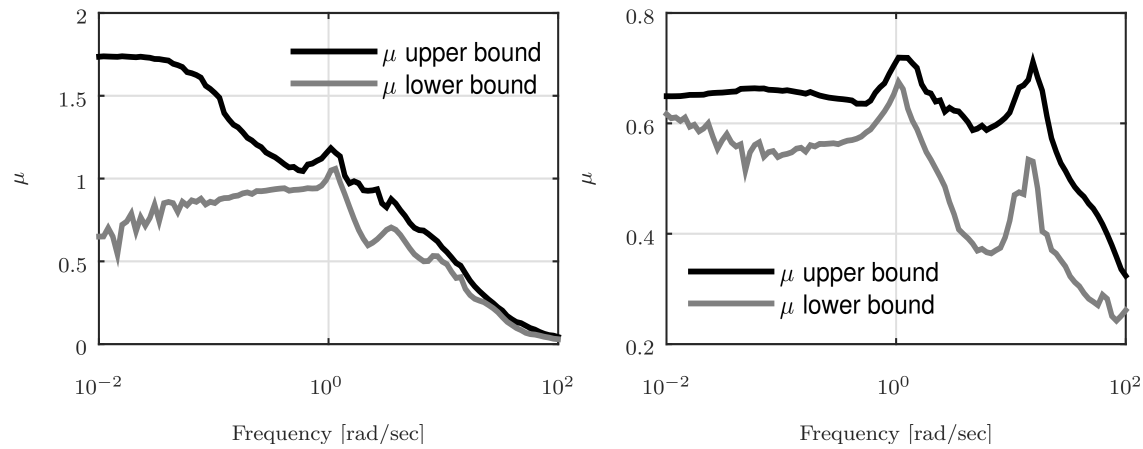
~~To reduce the controllers' complexity, thus making them computationally less demanding,~~ *Indeed* an order reduction *method* was implemented based on the Hankel norm [19]. The reduction provided an H∞ controller with order 35 and a μ-synthesis controller with order 52, ~~capable of achieving the same stability and performance results as the original high-order controllers.~~ *which is still a significant difference in terms of complexity between the two controllers.*

IV. Controllers stability and performance evaluation

In this paper, the two augmented systems are compared with respect to the PAV reference dynamics by evaluating the nominal (without model uncertainties) performance and the nominal handling qualities. The focus on the nominal results is related to the experiment presented in the second part of the paper. This experiment was conducted without taking into consideration ~~model's~~ *model* uncertainties, noise and disturbances to allow for a clear comparison of the two augmented systems with respect to the PAV reference dynamics. Therefore, robust performance analyses are beyond the scope of this paper and will not be considered here. The interested reader can find these analyses in [20]. However, robust stability analyses will be presented in this paper as they provide insights that are crucial to justify some of the obtained results.

A. Stability

Nominal stability was achieved by both H∞ and μ-synthesis controllers *by design.* ~~However,~~ Robust stability against model parametric uncertainties ~~was achieved by the μ-synthesis controller only.~~ *can be assessed by analyzing the structured singular value μ [14].* The parametric uncertainty matrix of the helicopter model was here normalized to have an infinity norm equal to 1. Therefore, according to the theory presented in [14], robust stability against parametric uncertainties could be ensured for augmented systems with structured singular value (μ) less than 1. ~~As can be seen~~



(a) H∞ augmented system **(b) μ-synthesis augmented system**

Fig. 2: Structured singular value (μ) lower and upper stability margins

~~in Fig.~~ Figure 2 *shows upper and lower bounds of the structured singular value for the H∞ and the μ-synthesis controllers.* The H∞ augmented response reaches a maximum value of μ equal to 1.734. This means that the stability of the system can be preserved for uncertainties with infinity norm less than $1/1.734 = 0.58$, thus robust stability is not guaranteed for all uncertainties of the system. ~~On the other hand,~~ The μ-synthesis control technique achieves instead a maximum value of μ equal to 0.724. Therefore, the stability of the system is guaranteed for uncertainties with infinity norm less than $1/0.724 = 1.38$, which includes all uncertainties of the system. *From this result it can be concluded that the μ-synthesis controller achieves a significant better result in terms of robust stability with respect to the H∞ controller. This is another crucial aspect that must be taken into account if an actual implementation on a real helicopter is considered.*

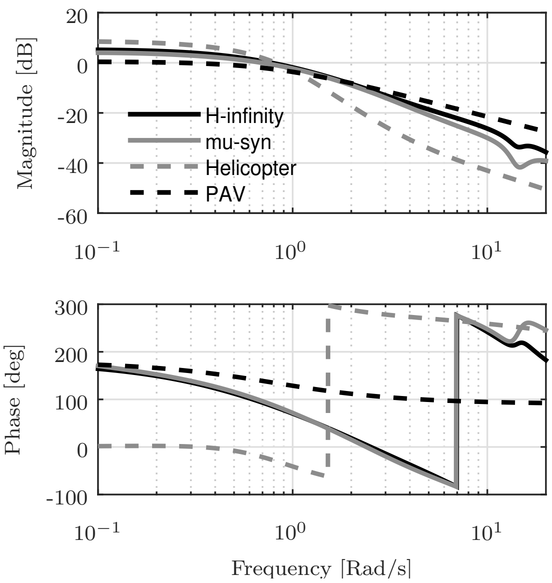
B. Nominal Performance

The nominal performance of the implemented controllers was evaluated by considering the infinity norms of the nominal closed-loop augmented systems. For the H∞ augmented system, an infinity norm value equal to 0.865 was obtained. The nominal μ-synthesis augmented system achieved an infinity norm value of 0.929. Both values are less than 1, which corresponds to good levels of disturbance, noise rejection and satisfying reference response tracking. However, the H∞ augmented system achieved a better result than the μ-synthesis system, *which corresponds to a better match with the desired PAV reference dynamics.*

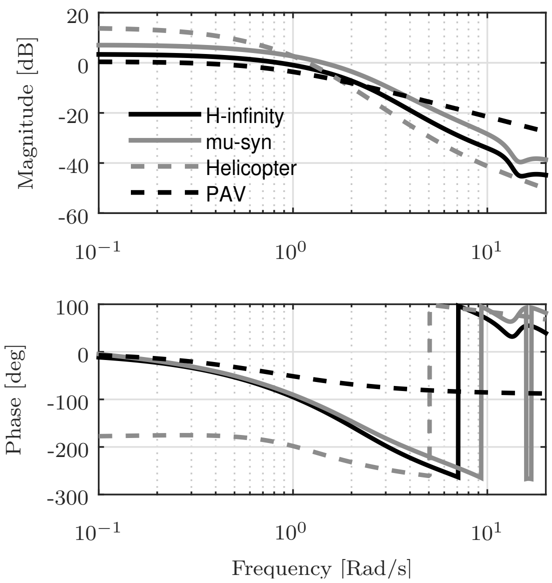
The frequency responses in Figs. 3-4 reflect this result. These plots show the nominal frequency responses of the original identified helicopter model (Helicopter), of the two augmented control systems (H∞ and μ-synthesis) and of the reference model (PAV). ~~The phases are shown in a way that allows for~~ *The phase plots are constrained to lie within a window of* 360 *degrees to simplify the* comparison even when a large delay is present in one of the frequency responses. Figure 3 shows the controllers' capability of modifying the original helicopter responses to match the PAV reference responses within the frequency range where the helicopter model is valid (0.1-16 rad/sec). However, ~~a noticeable delay is introduced~~ *at high frequencies both controllers fail to compensate for the large helicopter phase delay* in both ~~the~~ longitudinal and ~~in the~~ lateral axes ~~by both controllers~~ (Figs. 3a-3b). A good match is achieved *instead* by both augmented systems in the vertical axis (Fig. 4a) throughout the entire frequency range of interest. Also the yaw axis response (Fig. 4b) shows a very good match, although the phase of the μ-synthesis augmented system *slightly* diverges from the reference at high frequencies.

C. Handling Qualities analysis

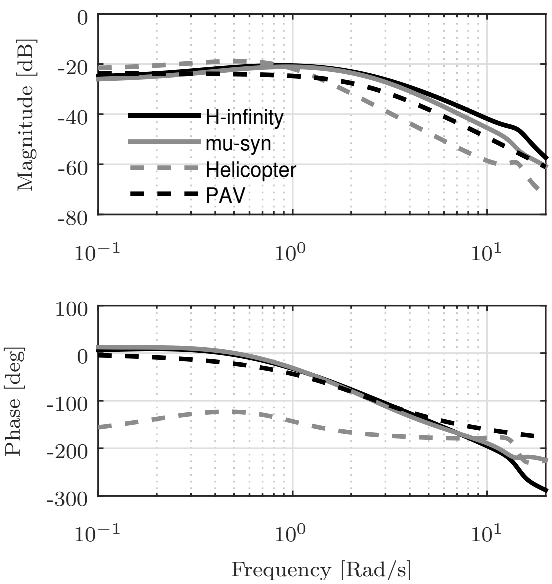
~~Another comparison in terms of nominal performance is made in this paper with a handling qualities analysis.~~ *Handling qualities analysis is another tool that can be used for comparison between the two augmented systems in terms of nominal performance. The ADS-33E-PRF [16] is generally adopted to rate rotorcrafts HQs in three levels:* ~~It is reminded that in ADS-33E-PRF three levels are defined to rate helicopters handling qualities:~~ Level 1 corresponding to desirable handling char-



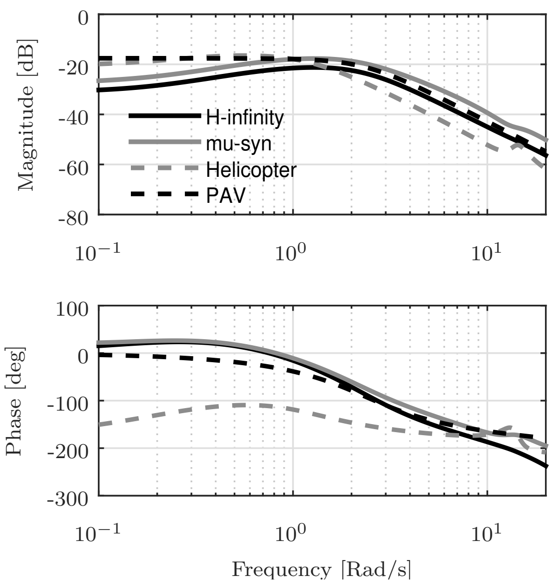
(a) longitudinal axis u/δ_{lon}



(b) lateral axis v/δ_{lat}



(c) pitch axis θ/δ_{lon}

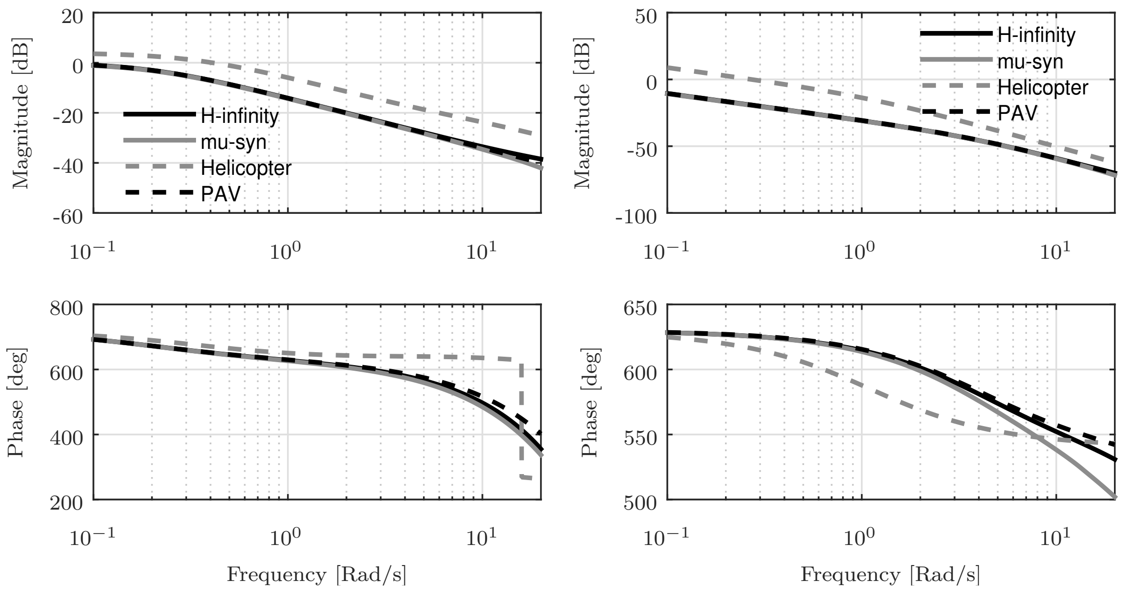


(d) roll axis ϕ/δ_{lat}

Fig. 3: Bode plot nominal system responses

acteristics, Level 2 corresponding to adequate handling characteristics, and Level 3 corresponding to undesirable handling characteristics.

The ADS-33E-PRF short-term bandwidth (ω_{BW}) and phase delay (τ_p) parameters are considered here to compare the implemented augmented systems with respect to each other, ~~with respect~~ to the original helicopter model and ~~with respect~~ to the reference PAV model. *Figure 5 shows the*

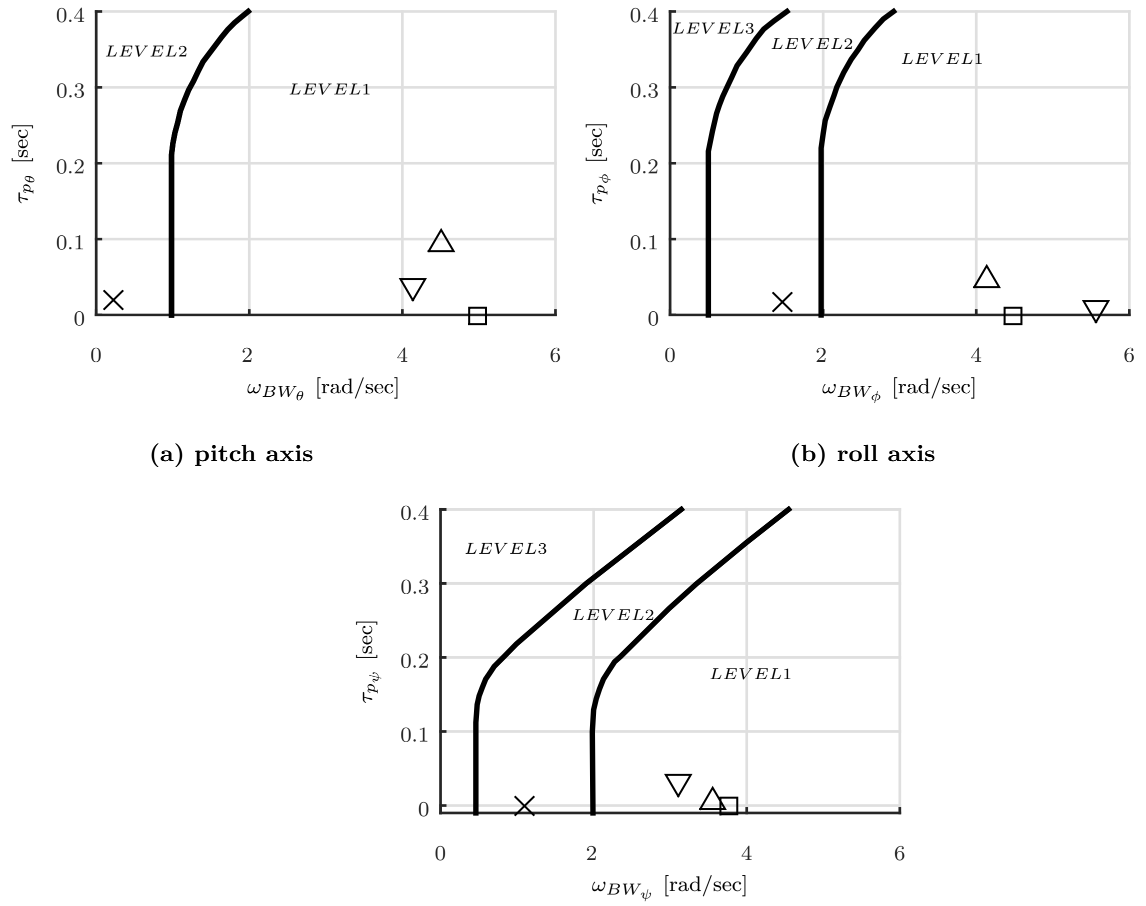


(a) vertical axis w/δ_{col} **(b) yaw axis** ψ/δ_{ped}

Fig. 4: Bode plot nominal system responses

boundaries between the three levels suitable for small-amplitude attitude changes in hover and low speed flight condition. As can be seen in Fig. 5, the identified helicopter model shows adequate HQ performance (Level 2) in all axes (pitch, roll and yaw), while the reference responses defined for PAVs have all Level 1 desirable HQs performance. The plots show how well the augmented control systems are able to resemble the HQs of the PAV reference model in all three axes. Both augmented systems are able to achieve Level 1 HQs. The two augmented control systems achieve comparable results in the pitch axis (Fig. 5a), whereas the H∞ performs better in the roll and in the yaw axes (Figs. 5b-5c). This is in agreement with the results shown in the frequency response plots (Figs. 3-4).

From these results it can be concluded that both augmented systems closely resemble the PAV responses although some discrepancies *bandwidth and phase delay* exist. At this stage, no information is available to assess whether these discrepancies are negligible. Therefore, it cannot be concluded yet if the implemented augmented systems can be considered suitable for inexperienced pilots and can allow them to reach similar performance and workload levels achieved with PAVs.



(a) pitch axis **(b) roll axis**

(c) yaw axis

Fig. 5: ADS-33 nominal system; $\times$ = Helicopter; $\square$ = PAV; $\triangle$ = H-inf; $\triangledown$ = mu-syn

D. Discussion

The results presented in the previous sections allow for comparisons between the two implemented augmented systems in terms of robust stability and nominal performance. The unachieved robust stability of the H∞ augmented system is an important point to be considered if an actual controller has to be implemented. This result can be due to the fact that the H∞ method does not include any uncertainty information in the control design. As a result, controllers implemented with this method usually guarantee robust stability against disturbances and noise but not against model parametric uncertainties. On the other hand, the μ-synthesis control technique includes the uncertainty block in the design, giving the possibility to achieve robust stability.

Nominal performance requirements were ~~satisfactorily~~ achieved by both controllers, which were able to resemble PAV's reference responses as far as allowed by the dynamical limits of the helicopter model. Furthermore, both augmented systems achieved Level 1 HQs in all axes. However, the H∞ augmented system achieved better nominal performance than the μ-synthesis system. This result ~~could be~~ *was* associated with the μ-synthesis system's capability of achieving robust stability. ~~Probably,~~ *Therefore,* the μ-synthesis optimization favored robustness over performance.

However, some discrepancies were observed between the augmented systems and the PAV reference model. *Since the boundaries of the ADS-33E-PRF have been defined for experienced pilots and no definitions exist in literature concerning HQs levels for inexperienced pilots*, a theoretical assessment of the registered discrepancies could not be performed at this stage.

~~For this reason~~ *Therefore*, an experiment was designed to validate whether the implemented augmented systems could be considered suitable for inexperienced pilots and could allow them to reach similar performance and workload levels achieved with PAVs. The results of this experiment will be presented in the next sessions and will inform the main research question posed in this paper as to whether civil light helicopters can be transformed into PAVs accessible to inexperienced pilots.

V. Human-in-the-loop experiment

The experiment presented in the following was performed at the Max Planck Institute for Biological Cybernetics in Tübingen, Germany. The experiment aimed at measuring subjective and objective performance and workload in piloted closed-loop control tasks performed by pilots without any prior flight experience.

A. Apparatus

The experiment was performed with the use of the MPI CyberMotion Simulator (CMS), shown in Fig. 6a. The CMS is a 6 DOF robotic arm mounted on a linear rail (KUKA Roboter GmbH), with a custom-built cabin mounted at the end-effector and equipped with an additional motion axis [21]. This 8 DOF motion simulator allows for highly realistic flight scenarios to be simulated as a result of its high ~~dexterity~~ *agility* and the large motion envelope. The enclosed cabin offers a field-of-view of approximately 140° horizontal and 70° vertical that allows for a virtual environment to be projected. For the experiment presented here, the cabin (Fig. 6b) was equipped with a pilot seat, a conventional center-stick cyclic, a collective lever and rudder pedals ~~(Wittenstein GmbH, Germany)~~. Stiffness and damping force were tuned for each control axis with the help of a helicopter pilot until a realistic and natural feel was obtained.

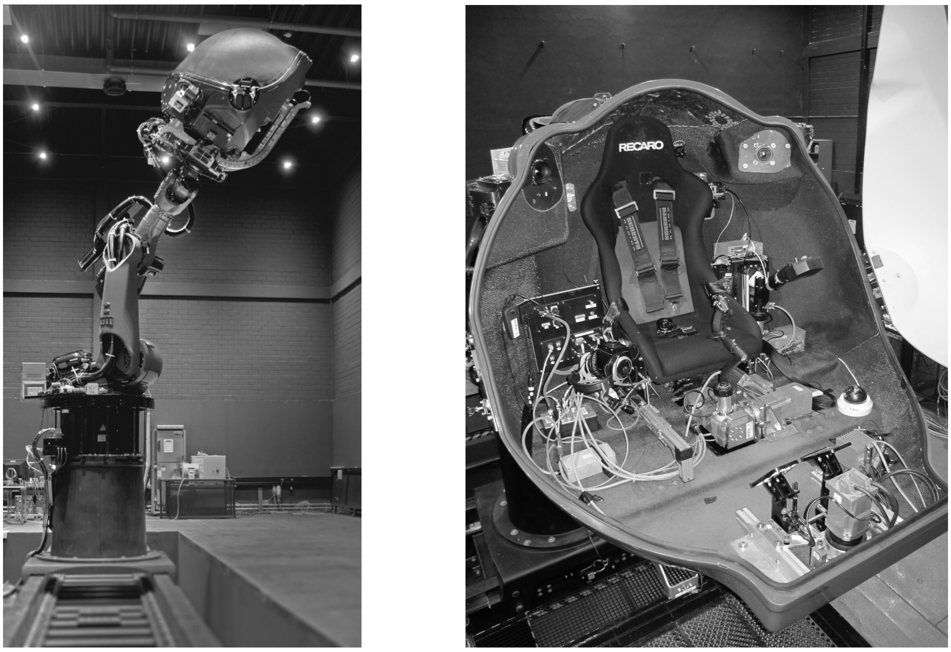
A motion cueing algorithm (MCA) was used to control the simulator within its motion envelope. The MCA is based on washout filters able to convert the motion of a simulated vehicle into simulator command inputs. ~~Here,~~ The washout filters were selected as second-order high-pass filters. ~~and Their~~ *Two sets of washout gains were employed. One set was tuned for the helicopter dynamics* ~~gains were manually tuned~~ based on evaluations given by *an experienced* helicopter pilot. ~~for the helicopter dynamics,~~ *Another set for the augmented dynamics and the PAV was tuned instead based on evaluations given* by three non-experienced pilots. ~~for the augmented dynamics~~. The tuning was done to ensure a coherent motion with respect to the visual cues provided during the experiment*, therefore avoiding false-cueing issues that could lead to motion sickness conditions.*

A visual scenery was presented inside the simulator cabin during the experiment (Fig. 7). The scenery was implemented with Unity3D, a game engine developed by Unity Technologies [22]. The scenery consisted of an airport with specific features on the ground designed to allow for hover and lateral reposition maneuvers to be performed as described in the ADS-33E-PRF [16]. Two projectors were used to show the scenery inside the cabin. The projectors had an update rate of 60 Hz. The time delay of the visual cues was measured in a previous experiment to be approximately 40 ms [23].

B. Independent variables

The experiment was designed to evaluate four different models through piloted closed-loop control tasks performed by inexperienced pilots. The four models represented the independent variables of the experiment and were selected as: the identified helicopter model of an R44 Robinson Raven II in hover [8], the two augmented systems implemented in this paper, and the PAV model developed during the myCopter project by University of Liverpool [24].

The helicopter model was considered as a baseline to assess inexperienced pilots' capabilities



(a) **(b)**

Fig. 6: ~~**Sub-figure (a) shows the MPI CyberMotion Simulator. Sub-figure (b) shows the internal of the simulator cabin equipped with a pilot seat, a center-stick cyclic, a collective lever and rudder pedals.**~~
In sub-figure (a) the MPI CyberMotion Simulator. In sub-figure (b) the simulator cabin equipped with a pilot seat and the helicopter controls.

to perform demanding maneuvers, while controlling a model characterized by instability, non-minimum-phase and high control coupling.

The two augmented control systems (H∞ and μ-synthesis) were included to evaluate discrepancies with respect to each other to the PAV reference model, and to evaluate improvements with respect to the original helicopter model in terms of performance and workload.

The PAV model was selected as a reference to allow for comparisons with the augmented control systems.

C. Mission Task Elements

To evaluate the considered models, two different maneuvers were selected: the hover and the lateral reposition maneuvers. Both maneuvers, also called Mission Task Elements (MTE), were

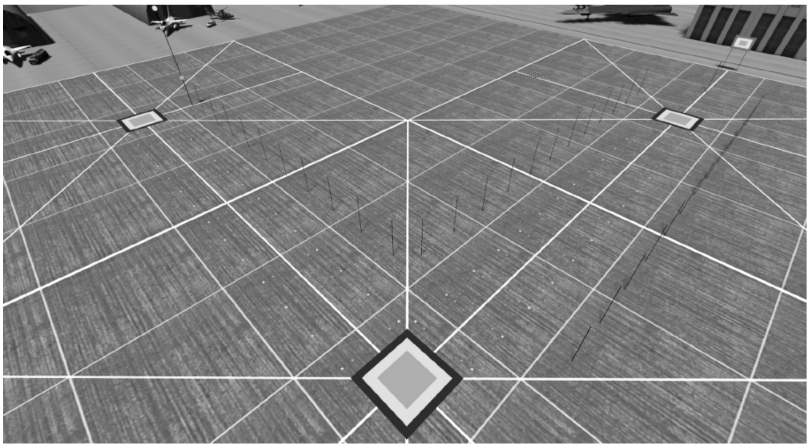


Fig. 7: Unity3D visual of airport with ADS-33E-PRF features for MTEs.

adapted versions of the original definitions described in the ADS-33E-PRF [16]. Changes were made based on the purpose of the experiment and on the limits of the selected models. For instance, the validity of the identified helicopter model within a 20 knots (10.29 m/s) velocity did not allow the MTEs to be performed within the time limits defined in the ADS-33E-PRF. Therefore, the time limit constraints *defined in the ADS-33E-PRF for expert pilots* were not taken into account in this experiment. Furthermore, definitions such as "desired" and "adequate" given in the ADS-33E-PRF were not adopted here. These definitions are generally used to rate the ability of experienced helicopter pilots to perform an MTE. However, in this experiment participants were not requested to achieve same performance as highly trained helicopter pilots.

The adapted MTEs were defined as follows.

- **Hover MTE:** This maneuver starts in a stabilized hover at an altitude of 25 ft (7.62 m) in front of a green sphere. The target is oriented 45 degrees right, relative to the heading of the vehicle. The pilot starts the maneuver by following a white line on the ground until the final target is reached. This, while maintaining the same initial altitude. A green square on the ground locates the target position with an accuracy of ±10 ft (±3.048 m). Furthermore, an outer yellow border is used to locate the target position with an accuracy of ±15 ft (±4.57 m). After reaching the target, a stabilized hover is to be maintained for 30 seconds.

  To aid the pilot in maintaining the right position during the hover phase, a hover board is provided 150 ft (45.72 m) in front of the target position. Furthermore, a pole with a red sphere on its top is placed halfway between the location of the target and the board. The pole has a height of 50 ft (15.24 m). The pilot can adjust the vertical and lateral positions by aligning the red sphere with the center of the board. Finally, a horizontal white line is placed on the ground to aid the pilot in maintaining the correct longitudinal position during the hover phase.

- **Lateral Reposition MTE:** This maneuver starts in a stabilized hover at an altitude of 25 ft in front of a green sphere. The initial longitudinal axis of the vehicle is oriented 90 degrees left with respect to the target position. A lateral acceleration followed by a deceleration has to be performed to reach the target, located 300 ft (91.44 m) right with respect to the initial position. Then, a stabilized hover is to be achieved and maintained for 5 seconds. During the entire maneuver, initial vertical position and heading have to be maintained.

  A green square on the ground locates the target position with an accuracy of ±10 ft, while an outer yellow border is used to locate the target position with an accuracy of ±15 ft. A straight white line on the ground is used to guide the pilot from the initial position to the target. Green and yellow markings are placed on the ground throughout the path to respectively indicate ±10 ft and ±15 ft distances from the straight white line. Throughout the path, black poles are placed with a hight of 25 ft and a spacing of 50 ft . The tips of these poles can be used as references to aid the pilot in maintaining the correct vertical position during the entire maneuver.

The two maneuvers defined in this way allow all control axes to be evaluated in both hover and low speed flight regimes. In the hover maneuver the longitudinal axis is particularly excited during the first phase in which the target position has to be achieved. Therefore, the capability to control this axis in low speed condition can be evaluated. The hover phase of the hover maneuver allows for an evaluation of the pilot's capability to stabilize the vehicle in zero velocity condition, which is highly influenced by the vehicles' axes-coupling and the vehicles' handling qualities.

In the lateral reposition maneuver the lateral control axis is mainly excited allowing for its evaluation in low speed condition. Moreover, requirements for maintaining initial attitude and height throughout the entire maneuver allow for an assessment of the pilot's capability to control yaw and vertical axes in low speed regime.

D. Dependent measures

To evaluate differences among the four models selected as independent variable, four main dependent measures were considered: objective performance, objective workload, subjective performance and subjective workload.

Objective perfomance metrics were defined as "position error" and "time to accomplish an MTE" that subjects had to minimize during each trial. For the hover MTE, the position error was defined as the absolute value of the difference between the target position and the vehicle position averaged over the 30 seconds duration of the hover phase. The position error was computed in terms of longitudinal, lateral and vertical errors. Furthermore, the heading error was included. This was computed as the difference between the vehicle's heading at the beginning of the maneuver, selected as reference, and the vehicle's heading during the hover phase, averaged over the 30 seconds duration of the hover phase. The time to accomplish the hover MTE was computed from the beginning of the trial until the target position was reached *and a stabilized hover was achieved. After this, a stable hover had to be maintained for* 30 *seconds. Therefore, the last* 30 *seconds were not considered as part of the time to accomplish the hover MTE.*

For the lateral reposition MTE, the position error was defined as the absolute value of the difference between the vehicle's position and the reference position averaged over the time to accomplish the maneuver. In particular, for the longitudinal axis, the current error was computed as the absolute value of the difference between the vehicle's longitudinal position and the reference, represented by a straight white line on the ground. For the vertical axis, the current error was computed as the absolute value of the difference between the vehicle's vertical position and the reference, represented by the tip of ten vertical poles placed throughout the path. For the lateral axis, the error was computed during the last 5 seconds during which a stabilized hover above the target had to be maintained. The lateral error was computed as the absolute value of the difference between the vehicle's lateral position and the target position averaged over the last 5 second. For the heading axis, the error was computed as the absolute value of the difference between the current vehicle's heading and the heading at the beginning of the maneuver, considered as a reference. The time to accomplish the lateral reposition MTE was computed from the beginning of the trial until the final target position was reached.

The objective workload was considered for both MTEs in terms of "amount of control activity", as defined during the myCopter project by University of Liverpool [3]. The amount of control activity represents the number of discrete control movements over the time necessary to complete the task. Discrete control movements are individual control deflections measured between two points where the control velocity is zero. In this experiment, control deflections smaller than one degree *($\sim$ 6% of the maximum control deflection)* were discarded to reduce measurements noise that could affect the analyses. The number of discrete control movements per second (control input rate) was first computed for each control axis (longitudinal stick, lateral stick, collective and pedals). Then, the four control input rates were averaged to produce a single value per trial.

Subjective metrics of workload and performance were also considered in order to have a comparison with the objective measures. For the subjective metrics, the NASA Task Load Index (TLX) was adopted [25]. The TLX allows for six workload aspects to be evaluated: mental demand, physical demand, temporal demand, performance, effort, and frustration. During the experiment, participants were asked to individually rate each workload aspect. Then, they were instructed to compare these aspects in order to evaluate their contribution to the overall workload. The resulting weighted ratings were finally used to compute for each MTE a single TLX workload score between 0 and 100, with lower numbers indicating lower workload.

E. Participants and instructions

Twenty-eight participants without any *actual* prior flight experience *as pilots* were invited to participate in the experiment: eighteen males and ten females. Their ages ranged from 24 to 39 years old. Furthermore, a former helicopter pilot was also invited for comparison with the other participants. The helicopter pilot had an experience of 110 flight hours and more than 500 take-offs and landings. His last flight training was in 1992. Most of his training was done with an Alouette II Sud-Est SE.3130 helicopter. He also trained for 4 hours in a simulator with a Bell UH-1D model.

Before entering the CMS, participants received an extensive briefing on the objective of the experiment. Furthermore, a general brief explanation was given about helicopter dynamics and helicopter control devices. Finally, participants were instructed on the MTEs to perform.

The main instruction participants received was to minimize both the time to accomplish the maneuver and the position error in both MTEs (hover and lateral reposition). *This instruction was stressed during the entire experiment to avoid the possibility that a participant would focus either on the position error or on the completion time, favoring one over the other.*

F. Experimental procedure

The experiment was designed considering a "between subjects" design. This means that each participant was assigned to a vehicle model randomly selected among the four considered in the experiment: identified helicopter model, H∞ augmented system, μ-synthesis augmented system and PAV model. In this way, the inexperienced pilots were divided into 4 groups of 7 participants each. The helicopter pilot was assigned to the experimental condition involving the control of the identified helicopter model.

Each participant performed both MTEs, of which the order was randomly selected. At the start of the experiment, participants trained for 20 minutes. During the first 5 minutes participants familiarized themselves with the control devices. ~~, by practicing executing the first MTE.~~ In this phase, every participant flew the PAV model ~~as it was best suited to familiarize the participants~~ *since already proven to be well suited for inexperienced pilots.* Then, one among the four vehicle models was randomly assigned to the participant for the remainder of the experiment. The ~~last~~ *following* 15 minutes of training were used to familiarize with the selected model *and to practice executing the first MTE. The motion of the simulator was activated in this phase only when the participant had achieved sufficient control capabilities to avoid safety issues. This because the CMS is capable of reaching extreme configurations and velocities that could result particularly uncomfortable for the participant.* During the training, participants were constantly instructed by the experimenter via headphones. At the end of each trial, a score was provided to motivate them to continue improving their performance and to maintain a constant level after their proficiencies had stabilized. The performance was displayed as "longitudinal, lateral, vertical and heading errors" and as "time to complete the trial". At the end of the training, participants rated the NASA TLX questionnaire. Then, the participants' performance was measured for five consecutive trials. Data were logged at a frequency of 100 Hz for later analysis. After these five trials, participants rated the NASA TLX questionnaire again.

A break of ~ 10 minutes was given to each participant before starting practicing on the second MTE. Then, a training of 10 minutes was provided to practice executing the second MTE. The training duration was shorted for the second MTE because participants had to practice on a different MTE but with the same control devices and the same model assigned during the first training phase. After training, data were collected for the second MTE in an identical fashion as for the first MTE. The experiment ended with a final rating of the NASA TLX questionnaire. Each participant completed the experiment in approximately 2 hours.

The duration of the two training phases was determined through a preliminary experiment, in which three inexperienced pilots were instructed to perform the two selected MTEs while controlling the PAV model. Results showed that after 20 minutes all participants were able to achieve adequate performance. Therefore, the same amount of training was assigned during the experiment for each model to allow for comparisons with the PAV model.

VI. Hypotheses

Three main hypotheses were considered in this experiment. The first hypothesis involves the identified helicopter model. This model was selected as a baseline for comparisons with the two augmented systems to validate their capability of improving the helicopter dynamics in terms of performance and workload. In particular, it was hypothesized that participants without any prior flight experience would not be able to stabilize and control the helicopter model, giving the short duration of the training.

The second hypothesis considered in this experiment concerns the PAV model. This model was implemented to allow inexperienced pilots to perform demanding maneuvers in hover and low speed conditions. Therefore, participants who received this experimental condition were expected to be able to control the model with adequate performance, already after the first training phase.

The third hypothesis concerns the two augmented systems implemented in this paper, H∞ and μ-synthesis models. These models were able to resemble response types and handling qualities of the PAV reference model. Nevertheless, some discrepancies were observed between the nominal augmented systems and the PAV model. In particular, the H∞ augmented system achieved slightly better performance results than the μ-synthesis augmented system, as shown in the handling qualities plots of Fig. 5. From this result, the μ-synthesis model was hypothesized to achieve lower performance relative to the H∞ system. In particular, the hover MTE was expected to be affected since the shown handling qualities result are associated with the hover condition.

VII. Results

In this section, results are presented of the 29 participants of the experiment. Two participants assigned to the helicopter model condition abandoned the experiment during the first training phase *conducted without motion of the simulator.* The *principal* cause was ~~motion sickness due to~~ their incapability of stabilizing the helicopter dynamics. *This* ~~which~~ induced abrupt and uncontrollable maneuvers, *which led to motion sickness for both participants.* Therefore, the data of these participants were excluded from later analyses.

In the helicopter model group only one inexperienced participant was able to perform the two MTEs. The other participants of the group were not able to control the helicopter model until the end of the experiment. This result is in line with the first hypothesis, in which the short amount of time provided for the training was assessed not sufficient to allow an ordinary inexperienced pilot to learn how to fly a helicopter. Conversely, all participants who received the PAV model were able to perform both MTEs, which is in line with the second hypothesis.

The following results will present the data collected over the last 5 trials from each participant. These data are averaged to have a single value for each participant. From these values, median and standard deviation are computed within each experimental group. The results will include the single participant that was able to perform both MTEs in the helicopter group. This result is only shown for the sake of completeness, and is considered an outlier which will not be discussed in the analysis. All other participants of the helicopter group will be not included in the results as they were not able to complete any trial. Despite the inability to accurately quantify the difference, it can be anyway concluded that the performance in the helicopter group was significantly worse than in all other conditions.

A. Hover MTE objective performance and workload

It is reminded that objective performance metrics were defined as "position error" in longitudinal, lateral, vertical and heading axes, and as "time to accomplish the MTE". The results can be seen in the boxplots of Figs. 8 and 9. In each box the central mark represents the median, while the edges are the 25^{th} and 75^{th} percentiles, respectively. The maximum and minimum values correspond to ± 2.7 times the standard deviation, respectively. Outliers are individually shown with a cross.

A multivariate analysis of variance (MANOVA) followed by a Bonferroni post-hoc test were performed to check for statistical differences in longitudinal, lateral, vertical and heading errors, between the two augmented systems groups and the PAV group. From the test, no statistical difference was found between the H∞ augmented system and the PAV reference model. The μ-synthesis augmented system performed slightly worse in longitudinal, lateral and vertical axes, as can be seen in Fig. 8. This result confirms the third hypothesis. However, a statistically significant difference was observed in the vertical axis only, as indicated in Fig. 8. In particular, the μ-synthesis performed statistically worse than the H∞ (p-value = 0.004) and statistically worse than the PAV reference model (p-value = 0.002). Nevertheless, it can be noticed that the difference between the medians in the vertical error is less than half a meter. This results show that both augmented systems were able to achieve performance results comparable to those of the PAV reference model in the hover MTE.

Figure 8 also shows the results of the actual helicopter pilot. The pilot achieved better performance than the medians of all other groups of participants. This means that ordinary PAVs pilots would need longer trainings than the one considered in this experiment to achieve performances comparable to those of experienced helicopter pilots. Nevertheless, it is worth to notice that some

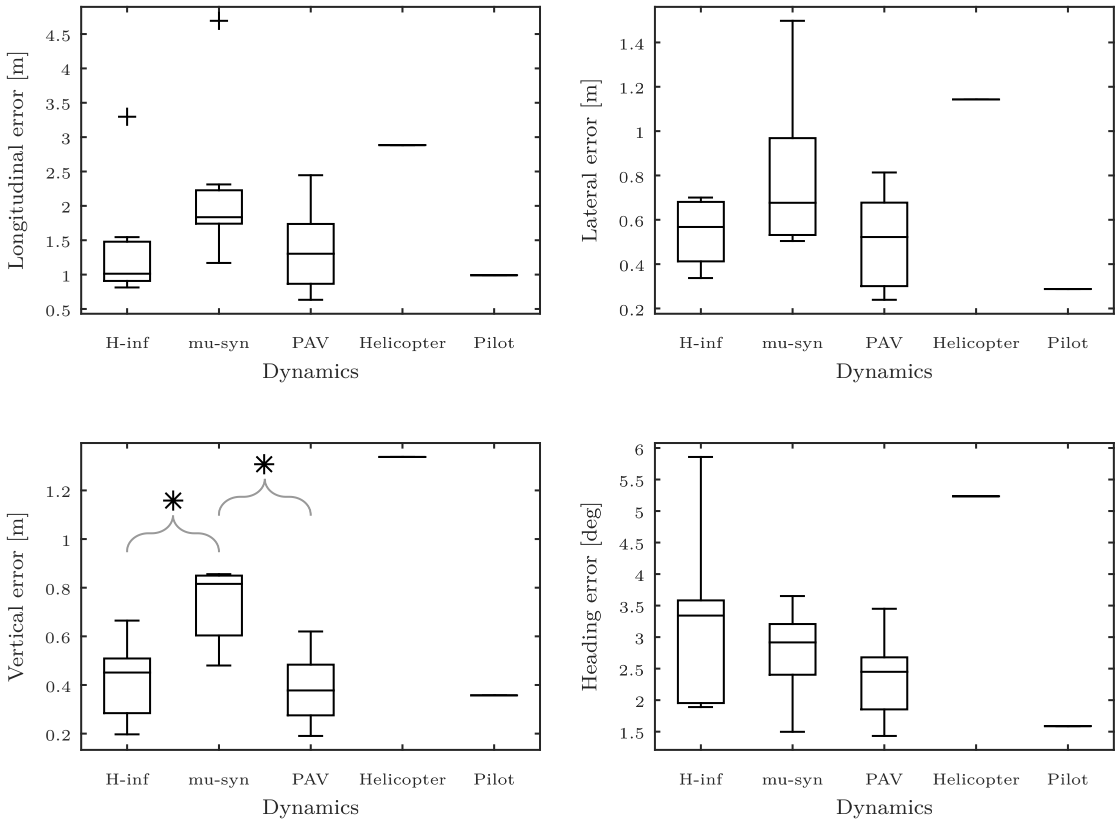


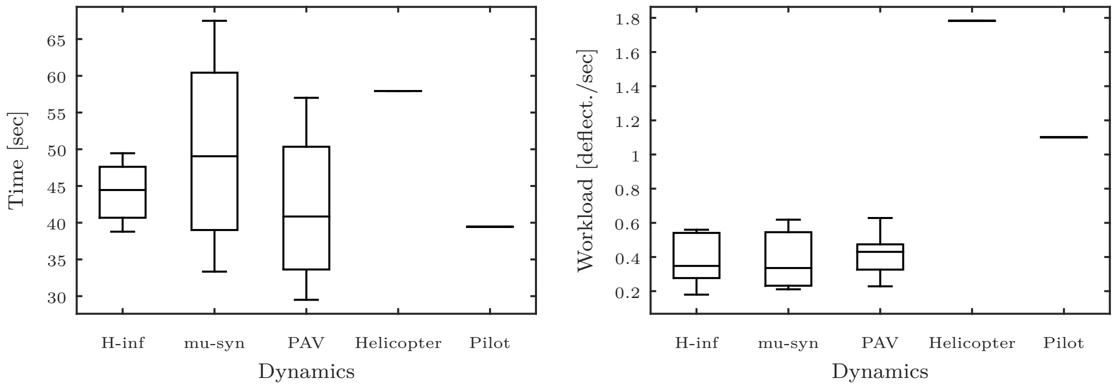
Fig. 8: ~~**Position error hover MTE. Significant statistical differences (p-value ≤ 0.05) between groups are indicated with a star and a bracket between the two groups for which the significant difference exists.**~~

Position error hover MTE. Significant statistical differences (p-value $\leq$ **0.05*****) between groups are indicated with a star and a bracket between the two groups.***

inexperienced pilots were able to achieve similar performance as the actual helicopter pilot.

An analysis of variance (ANOVA) test was also performed on the time to accomplish the maneuver. Also in this case, no significant difference was found between the H∞, the μ-synthesis and the PAV models (Fig. 9a). Furthermore, it can be noticed how the median of the PAV group is very close to the value achieved by the actual helicopter pilot.

An ANOVA test was finally performed on the objective workload, defined as the amount of control activity. No statistical difference was found between the two augmented systems and the PAV reference model (Fig. 9b), which means that also in terms of workload the two augmented



(a) **(b)**

Fig. 9: ~~**Sub-figure (a) shows the time to accomplish the hover MTE. Sub-figure (b) shows the objective workload measured as the averaged number of controls deflections per second.**~~

In sub-figure (a) the time to accomplish the hover MTE. In sub-figure (b) the objective workload in the hover MTE.

systems achieved results comparable to those of the PAV model. Furthermore, it is interesting to notice that the actual helicopter pilot needed a significantly higher control activity with respect to the other groups to correctly perform the hover MTE.

B. Hover MTE subjective rating

The boxplot obtained from the data collected with the NASA TLX questionnaire is shown in Fig. 10. Here, the data of all 29 participants are considered. The ANOVA test did not show any statistical difference between the augmented systems and the PAV reference model. This is in line with the results obtained from the objective workload measure. However, it can be noticed that subjects of the helicopter model group provided ratings comparable to those given by the other participants. Moreover, the actual helicopter pilot rated his overall workload lower than the medians of all other groups. This is in contrast with the results obtained in the objective workload analyses and will be addressed in the discussion section.

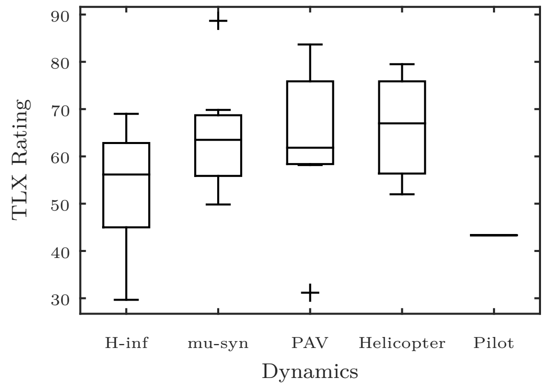


Fig. 10: NASA TLX subjective workload hover MTE.

C. Lateral reposition MTE objective performance and workload

The boxplots in Fig. 11 show the longitudinal, lateral, vertical and heading errors obtained from the data collected in the last 5 trials of the lateral reposition MTE.

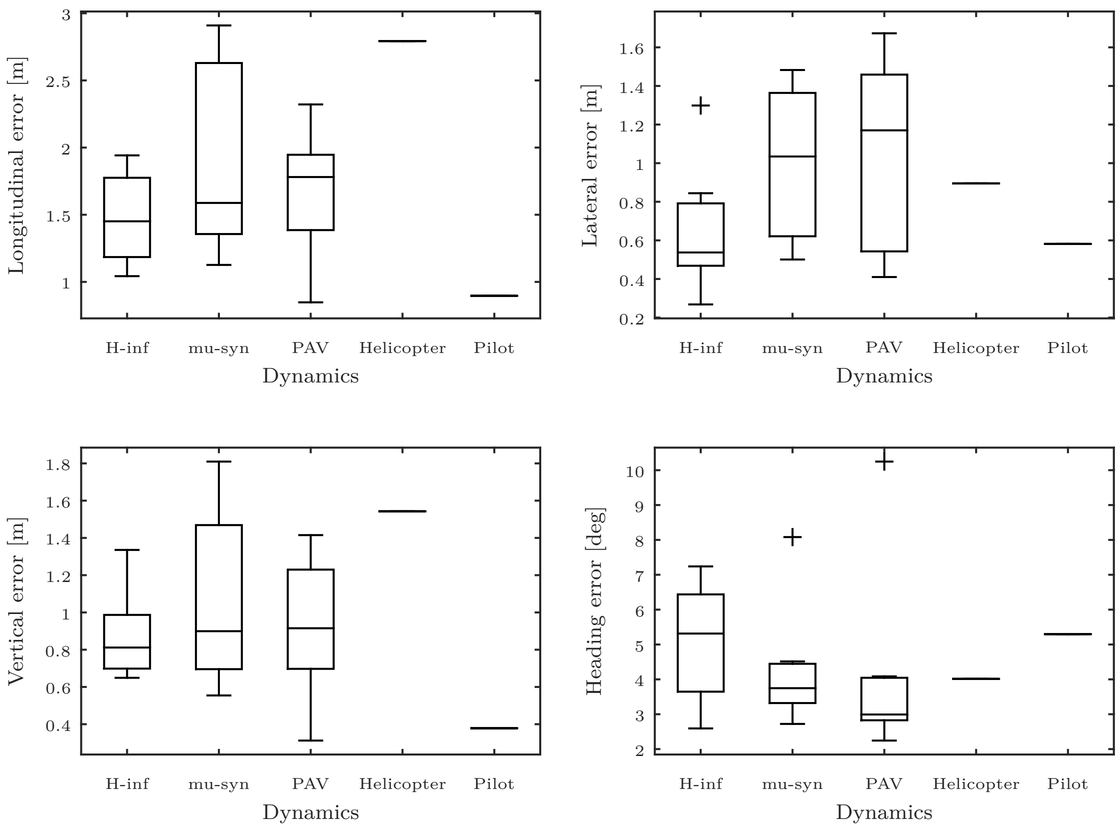
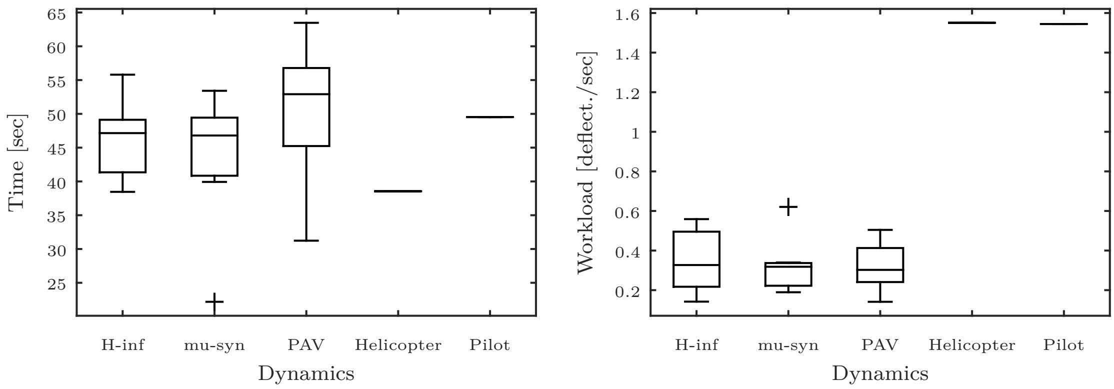


Fig. 11: Position error lateral reposition MTE.

A multivariate analysis of variance (MANOVA) followed by a Bonferroni post-hoc test were



(a) **(b)**

Fig. 12: ~~**Sub-figure (a) shows the time to accomplish the lateral reposition MTE. Sub-figure (b) shows the objective workload measured as the averaged number of controls deflections per second.**~~

In sub-figure (a) the time to accomplish the lateral reposition MTE. In sub-figure (b) the objective workload in the lateral reposition MTE.

performed to check for statistical differences between the two augmented systems groups and the PAV group. From the test, no statistical difference was found between the two augmented systems groups with respect to each other and with respect to the PAV model group. This is in line with the result obtained in the hover MTE. Therefore, it can be concluded that in both MTEs the augmented systems were able to achieve performance results comparable to those of the PAV reference model.

In the lateral MTE the actual helicopter pilot performed better than the medians of all other groups of participants only in the longitudinal and in the vertical axes. This result shows that the hover MTE was more demanding than the lateral MTE. Nevertheless, it confirms that a longer training would be necessary for inexperienced pilot to achieve same performance levels as those of experienced pilots.

An ANOVA test was performed on the time to accomplish the lateral MTE. As for the hover MTE, no statistical difference was found between the augmented systems groups and the PAV model group (Fig. 12a). *However, it is interesting to notice that the median in the PAV group is slightly higher. This result could justify the lower error achieved in the heading axis (Fig. 11). Probably,* *performing the maneuver in a slightly slower way allowed participants of the PAV group to better control the pedals during the entire maneuver.*

Finally, an ANOVA test was performed on the objective workload defined as the amount of control activity. Also in this case, no statistical difference was found between the two augmented systems and the PAV reference model (Fig. 12b). A larger amount of control activity was instead necessary for the actual helicopter pilot to correctly perform the task. This result is in agreement with that obtained in the hover MTE.

D. Lateral reposition MTE subjective rating

The boxplot obtained from the data collected with the NASA TLX questionnaire is shown in Fig. 13. Here, the data of all 29 participants are considered. As can be seen in the figure,

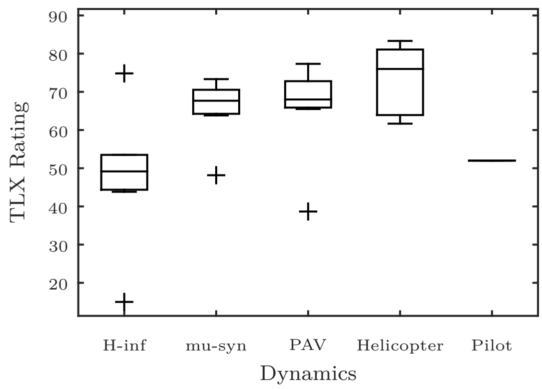


Fig. 13: NASA TLX subjective workload lateral reposition MTE.

participants of the H∞ group rated their overall workload lower than all other groups of participants. Furthermore, participants of the helicopter model group gave similar subjective workload ratings as the participants of the μ-synthesis and the PAV groups. As can be noticed, the rating of the actual helicopter pilot is very close to the median of the H∞ group and lower than the medians of all other groups of participants. These results are again in contrast with those obtained in the objective workload measure and will be discussed in the next section.

VIII. Discussion

The results of the experiment provided insights into the four selected models. In particular, the chosen MTEs allowed for evaluations and comparisons of the augmented systems (H∞ and μ-synthesis) with respect to the identified helicopter model and to the PAV reference model. The first important result was that 6 out of 7 inexperienced participants of the helicopter group were not able to achieve stability and correctly perform the selected MTEs. This result perhaps unsurprisingly confirmed the first hypothesis according to which 20 minutes of training were not considered sufficient to allow an ordinary inexperienced pilot to learn how to fly a helicopter. However, one inexperienced participant of the helicopter group was able to perform both maneuvers after the first training phase. This result was considered an outlier and was attributed to the previous participant's experience with control tasks involving helicopter-like dynamics in simulation.

It should be noted that the participant was able to quickly learn how to control the model by taking advantage of the use of the simulator in the training. This approach was considered more effective than the one generally used by ~~helicopters~~ *helicopter* instructors since participants had the possibility to lose control and crash. As such, they could learn from their mistakes and improve their performance after each trial. Clearly, this would not be possible in a real scenario. This approach was beneficial to only one participant of the helicopter model group. Nevertheless, it would be interesting to further investigate which factors are important during the learning process or whether few hours of flight tests in a motion simulator could be beneficial before training on an actual helicopter.

The second important result was that all participants of the PAV group and those of the two augmented systems were able to correctly perform the selected maneuvers. This result confirmed the second hypothesis and provided important information about the magnitude of discrepancy between the augmented systems and the PAV reference model. Objective performance and workload measures showed no significant difference between the H∞ augmented system and the PAV reference model in both MTEs. The μ-synthesis augmented system performed equally well as the PAV reference model in the lateral reposition MTE. However, a minor decrease in performance was observed in the hover MTE. Although this result confirmed the third hypothesis, a significant difference was observed only in the vertical axis with a difference of half a meter between the median of the PAV reference model and that of the μ-synthesis augmented system (Fig. 8).

From these results, it can be concluded that both augmented systems were able to resemble PAVs response types and handling qualities in piloted closed-loop control tasks. This positively answers the main question of this paper as to whether civil helicopters can be considered as possible candidates for PAVs when proper augmentation systems are in place. Therefore, the approach proposed here represents a valid alternative to the implementation of new vehicles with handling qualities considered well suited for PAVs pilots.

The third finding of the experiment was that the actual helicopter pilot achieved higher performance than the medians of all other groups of participants. This was expected, given the pilot's previous experience with actual helicopters and flight simulators. However, it was not possible to exclude beforehand whether participants of the PAV model group would achieve similar or better performance than the actual pilot. As a matter of fact, some participants of the $H\infty$ and the PAV groups performed as good as the actual pilot in the hover MTE. Nevertheless, this result showed that ordinary PAVs pilots would need longer trainings than the one considered in this experiment to achieve performances comparable to those of experienced helicopter pilots.

The final interesting finding was given by the NASA TLX questionnaire. Participants ratings on subjective workload and performance provided different results than those obtained from the objective measures. These results were attributed to the "between subjects" design of the experiment. This means that every participant had the chance to practice and perform maneuvers with only one of the four possible models. As a result of this, they rated the workload associated to the assigned experimental model, without having any reference for comparisons. Therefore, participants focused on different aspects like the difficulty at controlling simultaneously four control devices while flying in a 3 dimensional space, something they had never done before except for the actual pilot. Many inexperienced pilots considered the two MTEs as highly demanding tasks. Conversely, the actual pilot did not find any particular difficulty at performing the selected maneuvers. Because of these discrepancies, the NASA TLX questionnaire did not provide any additional information useful to evaluate the considered hypotheses and to answer the questions asked in this paper.

IX. Conclusions

This paper described the implementation of H∞ and μ-synthesis control techniques to augment an identified civil light helicopter model in hover. The resulting augmented systems were evaluated in terms of robust stability, nominal performance and handling qualities. Results showed that both control methods were able to modify responses and handling qualities of the identified helicopter model to resemble those defined for ~~PAVs~~ *Personal Aerial Vehicles (PAVs).* However, better nominal performances were achieved by the H∞ control method. Both augmented systems achieved Level 1 Handling Qualities. Nevertheless, some discrepancies were observed between the two augmented systems and the PAV reference model.

To assess the magnitude of these discrepancies and to further validate the two augmented systems, an experiment was performed by using the MPI CyberMotion Simulator. In this experiment piloted closed-loop control tasks were performed by pilots with no prior flight experience. Two control tasks maneuvers were considered: the hover and the lateral reposition ~~MTEs~~ *Mission Task Elements (MTEs).* Each participant was asked to perform both MTEs with one model among the identified helicopter model, the PAV reference model, the H∞ augmented system and the μ-synthesis augmented system. An actual helicopter pilot was also invited to perform the two MTEs with the helicopter model. This, in order to allow for comparisons with the other participants.

The experimental results were evaluated in terms of objective and subjective workload and performance.

The main conclusion was that both implemented augmented systems (H∞ and μ-synthesis) can achieve PAVs performance and workload in piloted closed-loop control tasks. This result positively answered the main question asked in this paper as to whether civil helicopters can be considered as possible candidates for PAVs.

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