Haptic Guidance with a Soft Exoskeleton Reduces Error in Drone Teleoperation

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Abstract. Haptic guidance has been shown to improve performance in many fields as it can give additional information without overloading other sensory channels such as vision or audition. Our group is investigating new intuitive ways to interact with robots, and we developed a suit to control drones with upper body movement, called the FlyJacket. In this paper, we present the integration of a cable-driven haptic guidance in the FlyJacket. The aim of the device is to apply a force relative to the distance between the drone and a predetermined trajectory to correct user torso orientation and improve the flight precision. Participants (n=10) flying a simulated fixed-wing drone controlled with torso movements tested four different guidance profiles (three linear profiles with different stiffness and one quadratic). Our results show that a quadratically shaped guidance, which gives a weak force when the error is small and a strong force when the error becomes significant, was the most effective guidance to improve the performance. All participants also reported through questionnaires that the haptic guidance was useful for flight control.

Keywords: Wearable Haptics and Exoskeletons, Teleoperation and Telepresence, Robotics.

1 Introduction

The recent years have witnessed a growing demand for drones in multiple fields such as agriculture, industrial inspection, logistics, and search and rescue [1]. However, despite the recent advances in drone design and sensing, their direct teleoperation still mainly relies on traditional remote controllers. These types of controllers are neither natural nor intuitive and require long training periods to be mastered [2]. In order to make drones more accessible to non-expert users and facilitate their direct control in demanding tasks such as inspection or rescue missions, several studies have investigated the use of gestures [3],[4]. In a previous study, the authors have identified an intuitive upper body movement pattern that naïve users exploited to fly a fixed wing drone [5]. This embodied flight style, which allows the user to directly control the pitch and roll of a drone using torso movements, reduces learning time and increases performance when compared to the use of a traditional remote controllers. In order to record torso gestures, the authors have developed the FlyJacket, a sensorised suit equipped with unobtrusive and removable arm supports, which allow people to fly with their arms spread out without experiencing fatigue or degrading the flight performance [6].

This paper presents the integration and test of a cable-driven haptic guidance in the FlyJacket. This work is motivated by several results showing that haptic feedback improves the task performance in many domains such as for surgery [7], rehabilitation [8] or sports [9],[10]. Haptic feedback has been implemented as a force feedback on joysticks to control flight for obstacles avoidance [11-13]. In those studies, an attractive or resistive corrective force relative to the distance between the drone position and the obstacle increases users' awareness and reduces collision occurrences. The flight immersion can also be enhanced by including the velocity of the drone in the haptic feedback [14],[15].

When the aim of the haptic feedback is to correct a trajectory, linear feedback control laws (e.g. proportional-derivative control) on the error between the robot position and a reference trajectory are typically used [7],[8],[16-18]. The stiffness of the guidance is a very important feature because a too soft guidance may not be effective while a too strong guidance may lead to user passivity [16],[17],[19]. Therefore, the force profile and stiffness play an important role and need to be studied in order to optimize the guidance provided by the haptic feedback

The kinesthetic feedback proposed in this paper aims to correct and guide the user

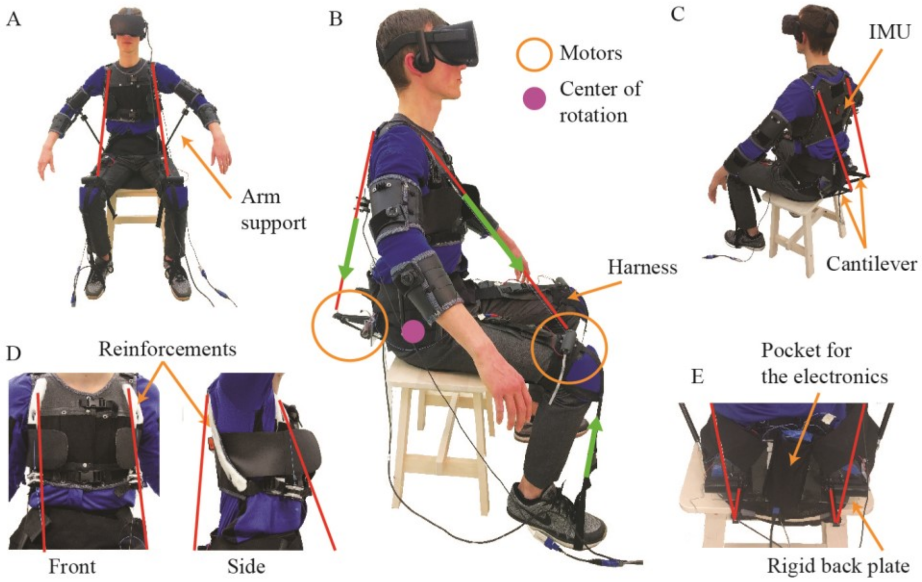


Fig. 1: FlyJacket with haptic guidance device. Cables are highlighted in red and the forces shown in green. (A) Front view. (B) Side view. (C) Back view. (D) Magnification on the torso part to highlight the reinforcements. (E) Magnification of the lower back part to highlight the back motors.

toward waypoints when flying a simulated fixed-wing drone using torso gestures. We investigated four different force profiles to determine their contribution on the reduction of the error between the drone and the waypoints. We studied how the addition of haptic feedback acts on the performance and on the workload of the user.

2 Haptic Guidance Implementation

2.1 FlyJacket Hardware

The FlyJacket is a soft exosuit developed for gesture based control of drones [6] (Fig. 1). This wearable suit tracks the torso orientation, and converts it into drone commands. The design of the exosuit and its ergonomics are suited for this flight style that has been identified has a natural and intuitive approach that naïve users adopt to fly fixed wing drones [5]. The user sits on a backless stool and bends his torso forward and backward in the sagittal plane, to control the pitch up and down maneuvers respectively. The user bends at the sides in the frontal plane to control the roll angle of the drone. The mapping between torso movements and drone commands is linear and the gains from the torso angle to the drone angle are 2.5 when pitching up, 1.5 when pitching down and 2 when rolling. Torso movements are recorded with an Inertial Measurement Unit (IMU) (Xsens, Enschede, The Netherlands) located in the middle of the back (Fig. 1 C). The exosuit is equipped with arm supports that allow the user to fly with the arms spread out without experiencing fatigue (Fig. 1 A).

Haptic guidance to the FlyJacket user was provided by a cable-driven system. With this system, four electrical motors (DC22S, gear ratio 6.6:1, Maxon Motor, Switzerland) pull on cables (Dyneema 0.4mm, Spiderwire, SC, USA, displayed in red in Fig. 1) attached to the user’s upper torso. In order to pull the torso according to the gestures performed by the user during flight, e.g. bending forward and backward with a center of rotation located on the hip (see Fig. 1 B), one motor is positioned on the distal part of each leg and two motors on each side of the lower back. With this antagonistic configuration, forces bend the user in both the sagittal and frontal planes. Both front motors are fixed to the legs with a harness system. To prevent the motors from sliding along the legs when pulling on the cables, they are maintained by a non-elastic textile band attached at its extremity to the user’s feet by the mean of a loop. Padding on the knee avoids user discomfort due to the force routing. The two back motors are located on the lower back and screwed onto a rigid plate to prevent them from moving (Fig. 1 E). Cantilevers made of 3D printed Acrytonitrite Butadiene Styrene (ABS) create a lever arm to induce forces that pull the user backward, instead of downward. Two non-elastic textile bands attached from the extremities of the cantilevers to the leg harness, passing on the back of the thigh, restrain the cantilever tips from moving when the back motors are pulling on cables. As the cables are attached on the torso part made of leather, reinforcements made of polymorph thermoplastic (Thermoworx Ltd, Ayrshire, Scotland, UK) have been inserted to stiffen the structure in order to prevent force losses and transmission delays (see Fig. 1 D).

The range of force of the haptic guidance should induce a torque higher than the passive stiffness of the human torso of around 10 Nm [20], in order to be able to move the torso of a fully compliant human. However, the user should also have full control of their body movements at any time. Therefore, we ensure that the maximal torque applied to the torso is much lower than the maximal torque a human can produce, which is around 150 Nm [21],[22]. As a comparison, the X-Arm 2, a rigid arm exoskeleton used to teleoperate a humanoid robot for extra-vehicular space missions, can produce up to 1/20th of the maximum human arm torque to deliver force feedback during manipulation [23]. Each motor of the FlyJacket's haptic system can produce up to 30 N of force, which corresponds to a torque of approximately 20 Nm for a 175 cm tall user when both motors of one body side are pulling together.

The four electrical motors are independently controlled by four transistors activated through a control board (Arduino Uno, Arduino, Italy). Thanks to the low gear ratio (6.6:1), motors are back-drivable. They are only activated when a corrective force is required to pull on the cables.

2.2 Guidance Profiles

The haptic guidance is based on the error (Δx) between the drone position and a predetermined trajectory at a predefined time in the future. For ease of visualization, Fig. 2 A is showing a 2D schematic of the distances, but the flight trajectories in the tasks are 3D. This error (Δx) is calculated as the scalar product between the vector from the drone to the look ahead point and the vector perpendicular to the direction of flight, pointing to the right for the correction in roll and up for the correction in pitch. The look ahead principle has been shown to enable stable vehicle control using external

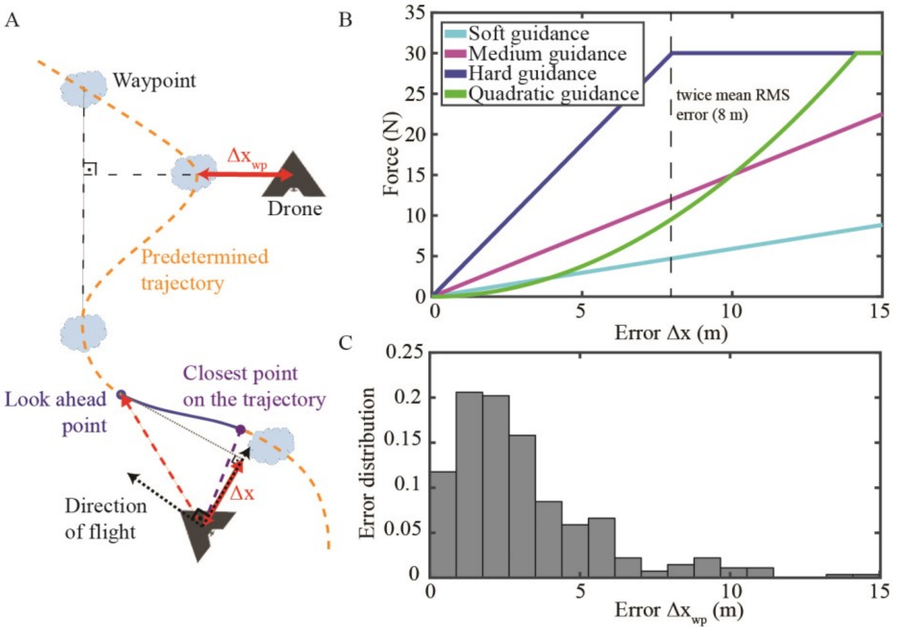


Fig. 2: (A) 2 D schema displaying the error (Δx) for the haptic guidance (measured throughout the task) and the error (Δx_{wp}) to measure the performance at each waypoint. (B) Force guidance over the error (Δx). (C) Waypoint error distribution (Δx_{wp}) found in previous experiment [6].

interfaces (e.g. remote controller) [17],[18]. In this study, participants were asked to follow a trajectory in the sky symbolized by small clouds (see Fig. 3 A), called waypoints, spaced apart by approximately 40 meters. The look ahead time was set to 3 seconds, which corresponds to a distance of 36 meters as the drone is flying at a constant speed of 12 m/s. The user receives an attractive force relative to their error (Δx), which indicates how they should move their torso to correct the drone position. As the four motors can be actuated separately, combination of forces on the front, back, and sides are achievable in order to correct the drone in pitch, roll or a combination of both. For example, as shown in Fig. 2 A, if the drone is positioned too far on the left regarding to the predetermined trajectory, front-right and back-right motors will pull on cables to exert a force to bend the user's torso on the right side. With this torso movement, the drone will roll on the right, and the error (Δx) will be reduced.

Four guidance curves were implemented to investigate which type of feedback could best correct torso movements during a flight task (see Fig. 2 B). We used three linear profiles with different levels of stiffness (hard, medium, and soft) and one quadratic profile that transitions from soft to hard guidance. These force profiles have been calibrated based on the Root Mean Square (RMS) and standard deviation (std) of the error (Δx_{wp}) measured at each waypoint from a previous study having a similar flight task but without guidance (see Fig. 2 A and C, and [6]). This error was the distance between the center of the waypoint and the point where the trajectory of the drone crosses a plane drawn perpendicular to the line connecting the previous and next waypoint [24]. The participant's performance was computed as the RMS of these distances over all waypoints of the task. The mean RMS error over all participants was 4.02 ± 1.62 meters (mean ± std).

The hard guidance has the advantage of giving a strong feedback to the user with a stiffness of 3.75 N/m. This guidance imparts the maximum force the motor can produce (30 N) at twice the mean RMS error found in previous experiment (Eq. 1). At more than 30 N, the motor is not able to produce more force, and it saturates as shown in Fig. 2 B. Since more than 90% of the errors (Δx_{wp}) found in the previous experiment [6] were smaller than twice the mean RMS error (8 meters, see Fig. 2 B), users seldom reach the saturation limit. This guidance strongly pulls the torso toward the orientation that would correct the drone's trajectory and immediately emphases every small error (Δx). However, this strong force may be unpleasant for the user as they may feel less involved in the control.

$$F_{\mathrm{hard}} = \begin{cases} 3.75 \cdot \Delta x, & |\Delta x| \leq 8 \\ 30, & |\Delta x| > 8 \end{cases} \tag{1}$$

In contrast, the soft guidance aims to hint which movements the user should perform to correct their orientation as the forces are too weak to influence the torso movement. This guidance has a stiffness of 0.59 N/m, which gives the maximal force at the mean error plus 30 times the standard deviation (Eq. 2). For small errors, the guidance force is very weak, which allows the user to make some mistakes without being strongly pushed back towards the reference trajectory as the hard guidance does.

$$F_{\mathrm{soft}} = \begin{cases} 0.59 \cdot \Delta x, & |\Delta x| \leq 51 \\ 30, & |\Delta x| > 51 \end{cases} \tag{2}$$

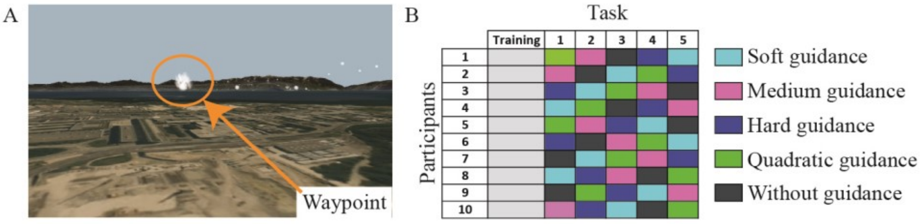
The medium guidance aims to be an intermediate guidance between hard and soft guidance and was designed to give half of the maximal force at the mean error plus 10 times the standard deviation, which corresponds to a stiffness of 1.5 N/m (Eq. 3).

$$F_{\text{medium}} = \begin{cases} 1.5 \cdot \Delta x, & |\Delta x| \leq 20 \\ 30, & |\Delta x| > 20 \end{cases} \tag{3}$$

The fourth proposed guidance has a quadratic shape. It combines the advantages of both the soft and the hard guidance. For small errors, it gives a weak correction force; therefore, the participant avoids being strongly perturbed. When the error becomes more significant, this guidance pulls the user strongly towards the reference trajectory. The force intensity was set to match the error of the medium guidance at half of the maximum motor force (15 N) as display in Fig. 2 B (Eq. 4).

$$F_{\text{quadratic}} = \begin{cases} 0.15 \cdot \Delta x^2, & |\Delta x| \leq 14 \\ 30, & |\Delta x| > 14 \end{cases} \tag{4}$$

2.3 Flight Experiment



Participants	Training	1	2	3	4	5
1	⬜	🟩	🟥	⬛	🟪	🟦
2	⬜	🟥	⬛	🟦	🟩	🟪
3	⬜	🟪	🟦	🟩	🟥	⬛
4	⬜	🟦	🟩	⬛	🟪	🟥
5	⬜	🟩	🟥	🟪	🟦	⬛
6	⬜	🟪	⬛	🟥	🟩	🟦
7	⬜	⬛	🟦	🟩	🟥	🟪
8	⬜	🟦	🟪	🟥	⬛	🟩
9	⬜	⬛	🟩	🟪	🟦	🟥
10	⬜	🟥	🟪	🟦	⬛	🟩

🟦 Soft guidance
🟥 Medium guidance
🟪 Hard guidance
🟩 Quadratic guidance
⬛ Without guidance

Fig. 3: (A) Flight environment. (B) Task order for each participant.

In order to evaluate the effectiveness of haptic guidance of the four different guidance profiles, ten participants (six men and four women, age 28.5 ± 4.5 years; mean ± std) flew a simulated fixed-wing drone using upper body movements. All participants tested the four types of guidance and flew once without guidance. They sat on a stool wearing the FlyJacket with arm support and virtual reality goggles (Oculus Rift, Oculus VR, Menlo Park, USA) that gave a first person view of the flight and wind sound for more immersion. They flew a fixed-wing drone in a simulator developed in Unity3D (Unity Technologies, San Francisco, CA, USA). The simulated drone physics were based on the eBee (SenseFly, Parrot Group, Paris, France), flying at a constant cruise speed of 12m/s which is the nominal speed of drones during imaging and mapping tasks.

Participants started with a short training without guidance composed of two tasks. At first, they had to follow the direction of an arrow positioned in front of them. The arrow was pointing consecutively “right”, “left”, “up”, and “down” twice. The goal of this task, which lasted one minute, was to make the participants perform every flight control movement at least once. The second task was one and a half minutes of free flight in a 3D reconstruction of our campus. The goal of the training was to enable the participant to feel comfortable with the control of the flight. For the evaluation part, participants were instructed to fly through 42 waypoints represented by small clouds (see Fig. 3A). These waypoints formed a trajectory in the sky and disappeared when they were reached. The waypoints sequence was randomized, but the number of maneuvers (up/down/right/left) was the same for every task. Each participant completed five trials, once with each guidance condition and once without guidance. They were not told which type of guidance they were to receive or what type they had received. The order of the guidance conditions presented to the participant was arranged so that each condition was placed twice at every position in the task order (see Fig. 3 B). The same succession of conditions was avoided as much as possible in order to remove learning effects. Participants' performance was computed as the RMS of the error (Δx_{wp}) of all waypoints.

At the end of each task, participants completed a Nasa-TLX questionnaire with pairwise comparison [25], which assessed the workload variation between flight conditions. At the end of the experiment, participants completed a final questionnaire asking which kind of guidance condition they enjoyed the most and the least, and which guidance condition they found the most and least useful (Table 1). The EPFL Human Research Ethics Committee approved the study and the participants provided written informed consent. All calculations for the data analysis done in this study were computed in Matlab (MathWorks, Massachusetts, USA). Graphs were also ploted in Matlab and aesthetically enhanced with Adobe Illustrator (Adobe Systems Incorporated, San Jose, CA, USA).

3 Results

3.1 Performance Results

Participant performance was measured as the RMS error reduction obtained by subtracting the RMS error of each task done with haptic guidance from the RMS error in

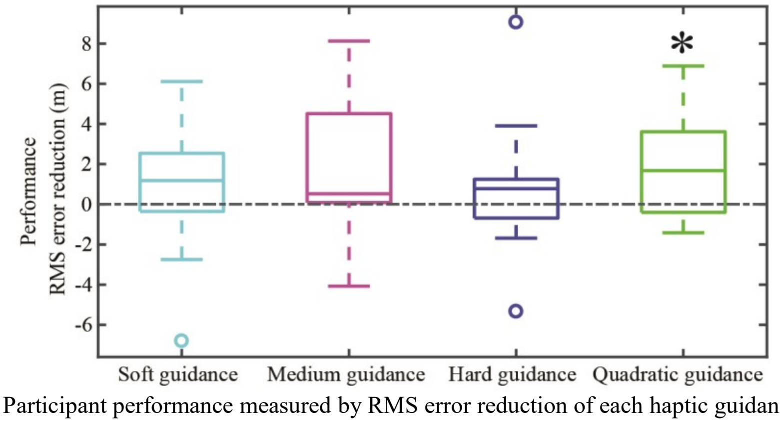


Fig. 4: Participant performance measured by RMS error reduction of each haptic guidance relative to without guidance (n=10). The central mark indicates the median, the bottom edge the 25th percentile and the top edge the 75th percentile. The whiskers show the most extreme data points not considered outliers (open circles). Asterisk (*) denotes $p < 0.05$.

the condition without guidance for each participant. This removes the performance level variation among participants and shows the effect of flying with a haptic guidance with respect to no guidance, i.e. what is the error reduction induced by the haptic guidance comparatively to flying without guidance. Therefore, a positive RMS error reduction means that the haptic guidance increases flight performance.

Results of Fig. 4 show that the median RMS errors for all types of haptic guidance are positive; the RMS error of the task was lower when performing the task with any type of haptic guidance than when flying without guidance. To determine if any of the guidance has a statistically significant effect on the error reduction, we ran a Wilcoxon Signed Rank Test using Matlab. The error reduction was significant for the quadratic guidance with a p-value of 0.0488. The three other guidance conditions, i.e. soft guidance (p-value = 0.4922), medium guidance (p-value = 0.0840) and hard guidance (p-value = 0.4316), do not show any statistical significance. However, due to the limited number of samples commonly gathered with human experiments, these results do not have a high statistical power. Therefore, we used a bootstrap metric. This non-parametric method generates the replication of 500 sample means (obtained by sampling with replacement 10 samples from the original dataset), which follow the same distribution as the data recorded during the experiment. This allowed us to obtain the empirical distribution for the sample mean. We then assessed whether the [2.5;97.5] quantile interval covers 0; the negation of the latter implying that the mean is significantly different than 0. We found that the quadratic guidance has a significant p-value of 0.0040, which supports the result found using the Wilcoxon Signed Rank Test done on our ten participants. In addition, the medium guidance also has a significant result with a p-value of 0.0260. The other two guidance conditions, i.e. soft guidance and hard guidance did not show any statistical significance with p-values of 0.2080 and 0.1860 respectively.

3.2 Subjective Assessment of Haptic Guidance

At the end of the experiment, participants filled a questionnaire specific to haptic guidance. The statement “I found the haptic guidance useful” was rated 6.08 out of 7 on the Likert scale from 1 (Strongly disagree) to 7 (Strongly agree). All participants rated between 5 and 7. They reported that it helped them anticipate maneuvers, particularly roll movements.

In the same questionnaire, they had to state which flight condition they found the most and the least enjoyable and the most and the least useful (Table 1). 6/10 participants found the hard guidance the least enjoyable versus 0/10 for the quadratic guidance. Also, half of the participants found the hard guidance the least useful versus 1/10 for the quadratic guidance. Notably, no participants found that the soft guidance, which provides the weakest force, was the least useful guidance.

Results for the most enjoyable and the most useful haptic guidance were more mixed (Table 1). 3/10 participants found the quadratic guidance the most enjoyable and the most useful and three others the soft guidance versus 0/10 for without guidance. As no participants rated the without guidance condition as the most enjoyable or the most useful, this result corroborates the high score of the guidance usefulness.

Table 1. Number of participants selecting the flight task as the most or least enjoyable and most or least useful in the final questionnaire (n=10).

In which task was haptic feedback:	Soft guidance	Medium guidance	Hard guidance	Quadratic guidance	Without guidance
the least enjoyable	1	2	6	0	1
the least useful	0	1	5	1	3
the most enjoyable	3	3	1	3	0
the most useful	3	2	2	3	0

3.3 Workload Results

As shown in Fig. 5 A, there are no statistically significant workload differences between flying with a haptic guidance and flying without guidance. There is also no difference in workload among haptic guidance types. Workload is composed of six different contributions: physical demand, mental demand, effort, temporal demand, frustration and performance, each of which can be analyzed separately [25]. The effort (Fig. 5 B) when flying with the medium and the quadratic guidance is significantly lower than when flying without guidance ($p = 0.0488$ and $p = 0.0352$ respectively). The same bootstrap metric used for the performance analysis with a replication of 500 sample means was applied. Both guidance show significance with $p = 0.0080$ for the medium guidance and $p = 0.0040$ for the quadratic guidance. The contribution of the effort on the general workload is 17%. The other workload contributions did not show any significant difference from zero and between guidance conditions.

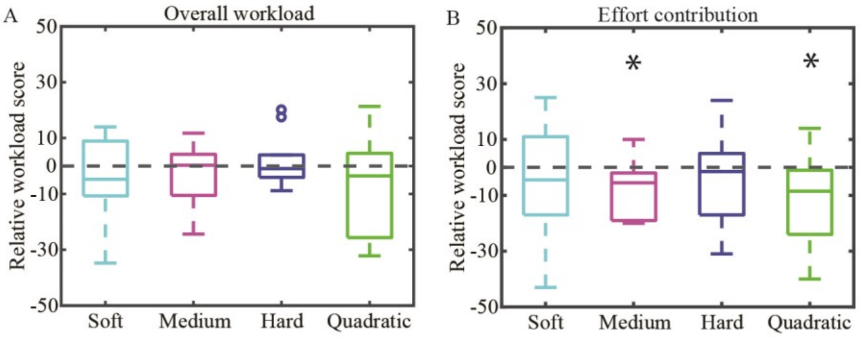


Fig. 5: (A) Overall workload found from the Nasa-TLX questionnaire, which includes contribution from the effort. See Fig. 4 for boxplot explanation. (B) Effort contribution. (*) denotes $p < 0.05$ (n=10), (open circles) signify outliers.

4 Discussion

This study demonstrated that receiving quadratically shaped haptic guidance when performing a flight task with the FlyJacket helped improve flight accuracy without increasing the workload. Out of the four force profiles tested, the quadratic profile was found to be the best over three linear profiles of different stiffness. In addition, our results showed that all users found haptic guidance useful when flying.

Having a quadratically shaped guidance, which gives weak force when the error is small and strong force when the error becomes large, is the most effective type of feedback to improve precision but also the one that requires the lowest effort. In comparison, the soft guidance was not only more enjoyable than hard guidance, but participants also found it more useful. Hard guidance was rated least enjoyable because participants felt the force was too strong. This may be because any small deviations from the nominal trajectories trigger large forces from the FlyJacket's haptic system, frequently perturbing the user's body. Consequently, they may not feel fully in control of their torso orientation, leading to the unpleasant feeling of being obstructed or to user passiveness [19]. The medium guidance, which is an intermediate guidance between the hard and soft guidance, had a more meaningful impact on the performance than the two extremes (soft and hard guidance) and significantly reduced user's effort.

Our study had a few limitations. We instructed users to follow waypoints during the evaluation task, and we calculated the performance measure only at these waypoints. However, in order to have a more precise understanding of drone dynamics, error in future studies could be measured by assessing the deviation from an overall trajectory, rather than discrete waypoints. To do so, additional experiments should be designed were the participant is able to see, for example by the mean of a line, the full trajectory in between the waypoints. We also restricted our tests to proportional controllers. Additional experiments could be performed to determine if adding a derivative term of the drone position to the quadratic or medium controller (e.g. PD controller) would further improve the performance.

By identifying an effective profile to reduce the error when following waypoints, this study provides the basis for further investigating the learning rate of the user with guidance in comparison to without guidance. The goal will be to understand if haptic guidance can accelerate the flight learning process and if this knowledge can be better retained by users. If so, having such a haptic guidance included in the FlyJacket could greatly reduce user training time. This could facilitate drone control and, therefore, make their use more accessible to non-expert users. For real world applications, we will also explore the use of haptic guidance for obstacle avoidance. This collision avoidance feedback can also be implemented by having the device pull the user's torso away from obstacles detected by vison or range sensors commonly embedded in commercial drones. While our current study utilized known reference trajectories for guidance, this type of force feedback can also be applied to constrain user motions to prevent maneuvers outside the flight envelope of the drone, for example to avoid stall conditions.

Acknowledgments

The authors would like to acknowledge Alexandre Cherpillod for the implementation of the error calculation in the drone simulator and thanks Claire Donnat for her help with the statistical analysis. This work has been supported by the Swiss National Center of Competence in Research in Robotics (NCCR Robotics).

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