DESIGN OF A HAPTIC OBSTACLE AVOIDANCE FOR LOW SPEED HELICOPTER OPERATIONS USING ACTIVE SIDESTICKS

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Abstract

Helicopter collisions with obstacles are one of the most frequent and most devastating causes of accidents. To avoid these collisions in low speed operations a "haptic ticker" cue in form of repetitive impulses as a force feedback was designed for an active sidestick. Various design questions were examined in pilot campaigns using a full flight simulator and four test scenarios. As a result, the pilots always knew which distance-based hazard area (green, yellow, red) they were in. Furthermore, the ticker is disruptive and roughly reduces the handling qualities from Level 1 to Level 2. It is therefore primarily activated as a hazard warning and not as a main input to control the distance. As a warning cue the ticker was evaluated as non-disturbing. The force threshold to detect the direction of a tick was determined. With tick strengths above this threshold, the direction is not recognized at all in around 2% of the ticks. For the remaining ticks, the accuracy with which the direction is recognized is about 15°. In the fourth scenario, obstacles were moved towards the hovering helicopter, potentially forcing a collision. However, with the ticker a collision occurred in less than 4% of the cases, instead of 84% without the ticker. The ticker was rated as very intuitive and worth recommending. When asked how many accidents of this kind could be prevented with this ticker, all five pilots independently estimated 75%.

1. INTRODUCTION

A consequence of the ability to hover and do vertical takeoffs and landings is that helicopters are operated close to the ground and thus close to obstacles. Picking up patients in urban areas, aerial work in the mountains or in the forest contain a high risk of collisions.

A review of the annual reports of German Federal Bureau of Aircraft Accident Investigation between 1999-2008 showed that 44 of 187 reported helicopter incidents (23.5%) included contact or collision with obstacles, [BFU2008]. Potential causes are that the crews simply overlooked the obstacles because they were not in the field of view or not visible because of degraded visual conditions (DVE), or because the pilot did underestimate the distance or did not recognize that the helicopter was drifting towards the obstacle. To deal with this problem, technological solutions were developed that detect obstacles with helicopter mounted sensors, [SEIDEL2008] and visualize them on a display [WAANDERS2015]. Nevertheless, it is likely that such a display will be overlooked, especially near the ground and when there are obstacles, since the visual focus is then mainly outside the cockpit. Addressing other than only the human's visual modality to warn about obstacles is already common in private cars: Here the distance is cued by an audio tone that is modulated in dependence of the distance allowing the driver to slow down or even stop the

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car before looking into a visual representation to see on which end of the car the obstacle was actually detected.

Another possibility is to use the haptic modality through tactile cues either generated by a tactile vest [CHEUNG2009] or belt [SZLOBOSZLAY2017] or by active inceptors to communicate distance and direction of the obstacle. Active inceptors contain a motor to actively generate the force-feel-characteristics of the inceptor instead of passive elements like spring and damper. But not only can these reproduce the characteristics of passive inceptors, but they can also be used to instantaneously modulate the forces and thus generate cues to warn or guide the pilot. [TAYLOR2008] gives an overview over the general functionality of active inceptors and typical cueing types, like soft stop, hard stop, detents, gate or stick shaker.

Academia has demonstrated various applications of tactile cueing with active inceptors for helicopters in flight and shown the potential for tactile envelope protection, workload reduction and increase of situational awareness. Industry has adopted the technology and equipped test aircraft or already started new developments or programs to retrofit existing types with active inceptor systems.

DLR equipped their inflight simulator ACT/FHS with active sidesticks. Among the demonstrated applications were a tactile cue for sink rate protection to avoid Vortex Ring State [ABILDGAARD2013], as well as a tactile cue for torque protection [MUELLHAEUSER2019]. The US Army test helicopter RASCAL was equipped with active inceptors and used in various research and development projects, including risk reduction testing for the later UH60-M [FLETCHER2008] and CH53-K [GREENFIELD2012] that is now equipped with active inceptors [SPOLDI2020]. In a cooperative activity under the scope of former the US-German Memorandum of Understanding (MoU), now US-German Project Agreement (PA) could demonstrate the ability to increase the handling qualities by an adaptation of the force-feel-characteristics of active inceptors to different upper control modes in flight [GRUENHAGEN2014]. One of the latest achievements of the cooperation was a common test program of US ARMY with DLR that compared different cues for a torque protection [MUELLHAEUSER2020].

On the industry side Boeing had retrofit single prototypes based on a CH 47, an AH 64 and a H6 and demonstrated various tactile cueing functions, including a very simply prototype of an obstacle avoidance [ENNS2013 and ENNS2016]. A completely new development program with active inceptors is the Bell 525 [SUNG2014].

Although several helicopters are or will be equipped by industry with active inceptors to allow tactile cueing, obstacle avoidance was yet not mentioned as a ready developed functionality. Assumingly because of the higher complexity with respect to required sensors and data processing, but probably also with respect to the higher difficulty in designing the right tactile cueing patterns. As these directly interfere with the controls when close to obstacles, when the risk of collision is high as well as the demand for precise controllability.

2. PREVIOUS WORK

Tactile Cueing with active inceptors for obstacle avoidance was already proposed by TU Delft for remote operation of unmanned aerial vehicles [LAM2009], providing solutions, like the Parametric Risk Field (PRF) as an approach to consider the speed or time-to-collision to identify relevant obstacles in the path of the helicopter. It was later adopted in prior work at DLR, see below [MUELLHAEUSER2017]. ONERA demonstrated a function that based on a potential field and provided continuous forces that would deflect the stick away from the obstacle [BINET2015]. Both ONERA approach and the DLR approach are discussed and compare in a common paper concluding with the need to further optimize the cueing patterns [RAKOTOMAMONJY2016].

The haptic obstacle avoidance cueing system previously developed by DLR presented the relative distance and the direction to those obstacles identified to be the most dangerous by

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tactile cues acting on the active cyclic sidestick [MUELLHAEUSER2017]. Two different cueing concepts were tested: A “force and stiffness” concept, inspired by [LAM2009], that generated continuous counter forces pointing from the obstacle towards the helicopter, that started when the distance between helicopter and obstacle was lower than a predefined minimum distance. It increased when the helicopter approached the obstacle. The other “ticker” concept instead generated short pulses, that were becoming more intense and repeated with increasing frequency when the obstacle distance got closer. Pilots rated the “force and stiffness” concept as neutral, as it served as a warning, on the one hand, but could impair the sensitivity of the controls, on the other hand. The “ticker” concept was rated very useful and satisfying. Due to its pulse pattern it was alarming and did not interfere with the controls. Nonetheless, some pilots stated that, although they could understand the direction or axis of the obstacle they could not understand the orientation, i.e. if the obstacle was in front or behind the helicopter. That is, why the following rules were defined to be considered in future optimizations:

- Effectiveness: The cue must be detectable by the pilot in terms of intensity and direction. Human pilot’s sensation of forces differs with the frequency and the ability of active inceptors to correctly present the intended tactile cue is restricted.
- Lack-of-nuisance: The cue shall disturb as less as possible and not more than acceptable. It must not lead to uncontrollability of the helicopter, i.e. provoke stick deflections which lead to dangerous changes of the helicopter flight state or uncontrollable pilot-induced oscillations.
- A clear definition of the intention of the cue: avoidance-by-guidance or avoidance-by warning?

Cues with sustained force, such as soft stops are therefore too invasive for most pilots in this critical flight phase. In addition, a sustained force generates a helicopter reaction which is undesirable.

The idea of communicating direction by applying asymmetric vibrations on the stick was also analysed by [BAELEN2020]. The authors compared symmetric triangular vibration shapes with asymmetric sawtooth shapes in a laboratory environment and could show that the necessary, or just-noticeable-difference (JND) of the cueing amplitude is less for the asymmetric shape.

3. TICKER DESIGN

The ticker is a haptic cue in form of repetitive impulses as a force feedback communicated with an active sidestick on cyclic control. The cue is comparable to the acoustic indications of a parking aid for cars. With sidesticks, however, it is possible to additionally indicate a direction. Also, the ticker’s frequency can be used to show a distance. Contrary to the parking aid for cars, it is less convenient to use the ticker as a main input to control the distance, because it can be disrupting for the pilot. This will be discussed in more detail below.

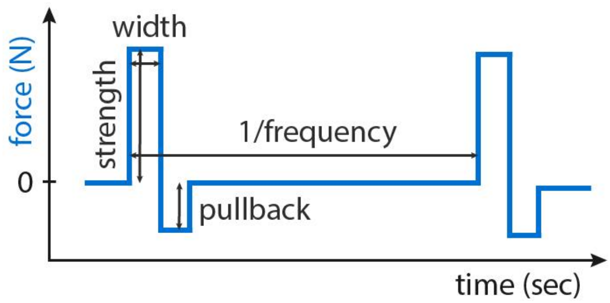

FIGURE 1: Parameters of the ticker’s force command.

The parameters of the base ticker are shown in FIGURE 1, they are referred to repeatedly in this paper. In blue the force signal is shown, that is commanded to the sidesticks to generate the basic ticks. This force corresponds to the force that the pilot would apply with his hand. With regard to the illustrated *strength*, there is a lower limit below which the direction of the cue is no longer perceived well enough. If the selected *strength* is too high, the ticker becomes annoying for the pilot. In addition, the resulting stick deflections can influence the movement of the helicopter. The same goes for large *widths*.

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However, if the ticker is pointing away from the obstacle, this may even be a desired behaviour. With a large *width*, the ticker feels clunky and less like a tick or impulse. If the *width* is too narrow, the hardware may not have enough time to overcome the stick's inertia. Since the ticker is created by impulse commands, which results in very short-term dynamics, the behaviour and how it ultimately feels also depends on the individual sidestick and its system. For the examinations described below we used 32 ms as a fixed *width* and only varied the *strength*. As a side note, the ticker was also tested with normal long pole sticks. However, the width had to be chosen so large to overcome the large inertia that it felt unacceptably clunky. Back to short pole sidesticks, the *frequency* parameter is less strictly limited in the meaningful range. It is usually set around the heartbeat of stressful situations. The *pullback* impulse is not mandatory, but it improves how the ticker feels for the user. It makes it sharper, clearer and less invasive. If the *pullback* is too large (>50% of *strength*), this often leads to confusion about the direction of the ticker. In that case the user does not know if the tick or the *pullback* indicated the direction.

The direction of the ticker can be designed to point towards-the-obstacle like a person who indicates "there is an obstacle"; or it can point away-from-the-obstacle like an autopilot or co-pilot that indicates or initiates an evasive direction. Here the away-from-the-obstacle indication was used, because it is expected to be more intuitive with the idea of an autopilot system in the mind. In addition, it corresponds with the control that the pilot must execute instead of contradicting it, thus a lower workload is expected. The pilots also had no problems with it in the simulator campaign described below.

In addition to the direction, the distance to the obstacle is also indicated to the pilot by using different *frequencies* for the ticker. As shown in FIGURE 2, there are three hazard areas – green, orange and red – with its associated ticker frequencies. If the helicopter enters the orange area, which is 1.5 rotor diameters away from the obstacle, the ticker will be activated with 2 Hz. The pilots or operators should be able to set the extent of the hazard areas individually. Different obstacle distances are to be expected based on the mission profile and depending on the individual pilot. As an example, in mountain rescue, they often fly closer than a quarter diameter to rock walls. In contrast, many other pilots rarely fly closer than two diameters to obstacles.

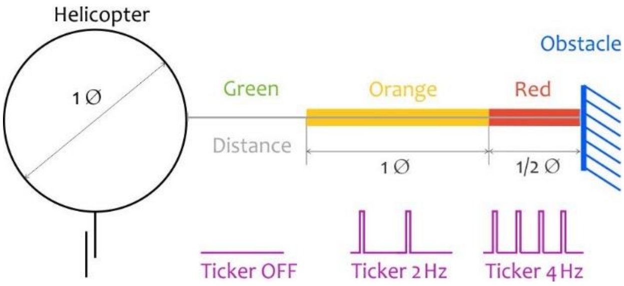

FIGURE 2: Design of the ticker's distance indication with different frequencies.

A general design idea here is that the ticker only activates as a hazard warning when obstacles have been overlooked and the pilot has flown closer to obstacles than wanted. The extent of the hazard areas must be set accordingly narrow. The reason for this is that the ticker can be annoying and should therefore not be used as a main input to control the distance. The investigations for this disruption are described in more detail below. There is also a button on the stick with which the pilot can deactivate the ticker.

As described, the ticker indicates the distance between helicopter and obstacle. This works well for low speeds such as hovering. However, with drift, the time to collision is a better predictor of the hazard rating of an obstacle, and even better is a risk value as used in [MUELLHAEUSER2017], which is a mixture of both, distance and time. The problem with this time or risk values is that they are harder to interpret by the pilot. In [MUELLHAEUSER2017] a risk value was indicated and the pilots where often confused about the obstacle location. To keep it simple at first and to have a working system as a starting point, larger drift rates are not yet considered here. However, the possibility of changing from distance to time or risk values was considered, and can be done simply by defining the extent of the hazard areas differently.

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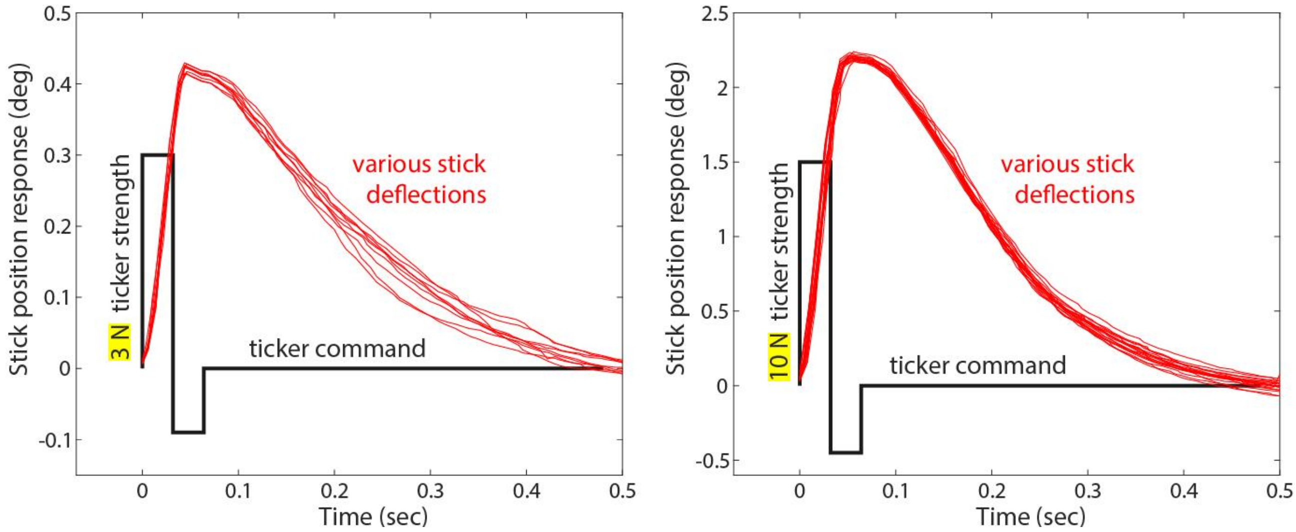

FIGURE 3: Stick deflection as a response to the force command of the ticker, with 3 N strength on the left and 10 N on the right.

Also note that the metric for selecting the most dangerous obstacle and the metric, which is displayed to the pilot, may be different. The ticker proposed here uses a risk value from [MUELLHAEUSER2017] to select the most dangerous obstacle, and for this, the distance is indicated to the pilot.

Although obstacle collisions are a 3D problem, the focus here was on rotor strikes in the 2D rotor level and less about collisions with larger sink or climb rates.

A requirement for the ticker is consistency across all situations. The ticker should "always feel the same". Problems with this can be caused by force-deflection-characteristics with varying gradients, non-linear sections or other haptic cues. Very dynamic control inputs and how the pilot holds the stick can also lead to inconsistencies. Some pilots grip with the whole hand, others only use the tips of index finger and thumb to hold the stick very loosely.

How the system reacts to the force command of the ticker, i.e. how the stick deflection behaves, also depends on (a) the individual short-term responses of the sidestick system, and (b) the interactions with the pilot's hand also play a role. Some measured deflections with hands off for 3 and 10 N ticker strength are shown in FIGURE 3.

The values of all currently used parameters for the ticker, as shown in FIGURE 1 and FIGURE 2, are summarized here:

- strength = 5 N,
- pullback = 30% of strength,
- width = 32 ms,

orange limit:

- frequency = 2 Hz
- distance = 1 Ø from obstacle (!)

red limit:

- frequency = 4 Hz
- distance = 0.5 Ø from obstacle

If no other values are given, these values are assumed in the following.

4. PILOT CAMPAIGNS

The campaign was carried out in DLR's Air Vehicle Simulator (AVES) with seven pilots. The AVES is a versatile research flight simulation facility providing a 6 degree of freedom hexapod motion system which enables the use of multiple cockpit layouts through a roll-on-roll-off system, [DUDA2013]. The dome projection provides a field of view of 240x95°. The Airbus EC135 cockpit has equal dimension and a similar instrumentation as DLR's research helicopter ACT/FHS (Active Control Technology / Flying Helicopter Simulation). Both the AVES and its helicopter cockpit are shown in FIGURE 4.

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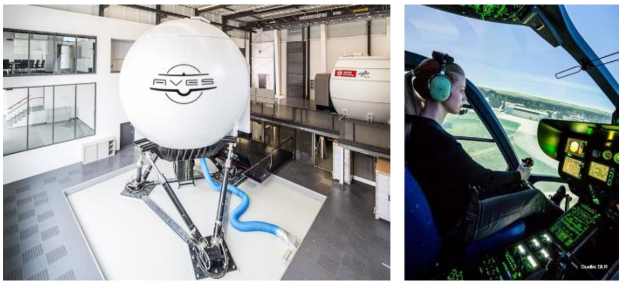

FIGURE 4: The Air Vehicle Simulator (AVES) with its EC135 cockpit at DLR Braunschweig.

All of the seven pilots were experienced test pilots with 2000-5000 flight hours. Five of them had a purely military background, of which three were German pilots and two from the United States. All pilots had operational experience with transport and utility helicopters, and three pilots also had operational experience with combat helicopters. All pilots had flying experience with search and rescue, mountain flight, sea flight, visual flight rules day and night, instrument flight rules, night vision goggles, winch and load hook.

Two campaigns were carried out. The first one was done with four pilots and was more of a fundamental nature. With three experiments, it was examined (a) whether and how well the distance is displayed, (b) how disrupting the ticker is and (c) how well the direction is indicated. With the experience gained, the ticker design was adapted so that the status described above resulted. With these adaptations the second campaign was carried out with five pilots. This campaign was about system and stress tests with moving obstacles, which force potential collisions.

5. DISTANCE TEST

To investigate the quality of the distance indication of the ticker design, simple tests were carried out. The pilot approached a known obstacle without seeing it, once backwards and once with strong brownout. This test was carried out in an artificially created "obstacle city", with all kinds of common obstacles, like trees, house walls, rock walls, power lines, wind turbines, cranes, cars, street and traffic lights and so on. At the beginning, each of the four pilots also had the opportunity to fly around freely in the obstacle city and to play around with the system, in order to first familiarize themselves with the simulated helicopter and then with the ticker cue. Here, too, the indication of the distance was tested by the pilots, but in a freer manner. Additionally, the distance feature was also tested in the second campaign, during the stress and system tests with moving obstacles.

In all these cases, the pilots were asked to talk about their current situation and communicate everything related to the ticker while flying. In addition, they were asked afterwards whether it was always clear in which hazard area they were currently in.

As result, all pilots always knew which distance-based hazard area (green, orange, red) they were in, thus an increase in situational awareness can be recorded. Furthermore, the false classification rate, to classify the hazard area, was zero in these tests.

6. DISRUPTION TEST

From the pilot's point of view, the ticker generates additional, disruptive forces on his most important control element, in one of the most critical situations of the mission. To test how disrupting and annoying the ticker is for the pilot, a hover MTE (Mission Task Element) in combination with the active ticker was used. The maneuver was repeated with different ticker settings in strength and frequency (see FIGURE 1) to investigate their effects on the disturbance. This also includes the question of whether there are acceptable settings at all and which are the limits for unacceptable settings.

The hover MTE is part of [ADS-33E-PRF]. The pilot's task is to first fly towards the hover point with 6 to 10 kn ground speed at an angle of 45°. There the helicopter should be stabilized and hovered for a certain time. In the vicinity, the pilot has visual cues about his deviation from the hover point. There are desired and adequate deviation limits in lateral, longitudinal, vertical and heading to evaluate the handling qualities. Following the maneuver, the pilot evaluates the Handling Quality Rating (HQR) using the Cooper-Harper

Rating Scale [COOPER-HARPER1969]. The ticker settings strength and frequency were varied for each maneuver but not changed during a maneuver. As a basis for comparison, maneuvers without an active ticker (Strength = 0 N) were also flown. There was no obstacle, so that the ticker was purely generic without any useful information. The direction of the ticker was changed similar to the second hand of a clock, but slightly faster and with random start direction. This test was carried out with attitude commands (AC) and a stability augmentation system (SAS) for yaw.

Each of the four pilots did the hover MTE ten times. For all resulting HQR's a multiple linear regression was made:

(1) $$\mathrm{HQR} = \begin{bmatrix} 1.84 \\ 0.21 \\ 0.62 \\ 0.032 \end{bmatrix}^{\mathrm{T}} \cdot \begin{bmatrix} 1 \\ \mathrm{str} \\ \mathrm{frq} \\ \mathrm{str} \cdot \mathrm{frq} \end{bmatrix}$$

with str = Ticker strength in N and frq = Ticker frequency in Hz. A visualization of this function is shown in FIGURE 5. It illustrates how the pilots rated the handling quality with the Cooper-Harper Rating Scale for different ticker settings. The mean absolute error between the data and the regression is 0.35 HQR and the maximal error is 1 HQR, which indicates that this regression is a good fit and a good predictor. With a deactivated ticker, the pilots rated 1 or 2 as HQR. Even a weak ticker reduces the HQR by 1 but stays in the satisfactory range. Due to stronger tickers, the handling qualities are only adequate, with the HQR being reduced by 2-4. In general, from a disruption perspective, the ticker should be designed as weak as possible.

One implication of the disturbance test is that the ticker is primarily used as a hazard warning for unnoticed obstacles or unwanted drift towards an obstacle. In contrast, the ticker should not be used as the main input to regulate the distance to the obstacle. In the latter case, the ticker would be active during the entire mission section (e.g. hover) and would be disruptive. In the first-mentioned case, on the other hand, the ticker is

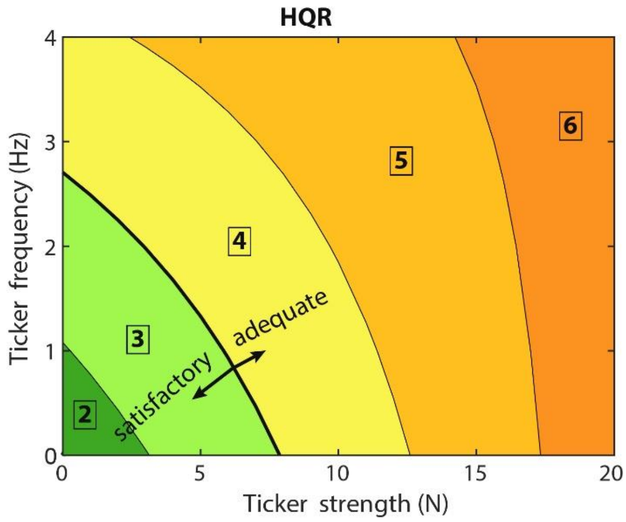

FIGURE 5: Regression of Handling Quality Ratings (HQR) for Hover MTE with active ticker. Ratings 4, 5 and 6 are level 2 handling qualities.

not active at all during normal operation, but only when critical limits are exceeded that were set by the pilot or operator. If the ticker is activated in this case, the pilot wants to fly out of the hazard area and thereby deactivates the disrupting ticker at the same time.

In the system test explained below, the ticker was used excessively as the just described hazard warning. Here, too, the pilots were asked how disrupting the ticker was on a scale from 0 to 6, where 0 = not at all and 6 = unacceptable. Two pilots rated 0 and the other three pilots rated 1. Therefore, the ticker with this design is considered to be acceptable in terms of disturbance.
Due to the relatively small number of pilots, regressions were also made individually for each pilot. The individual results are all very similar to each other and to FIGURE 5. So, the variation between different pilots was very small.

7. DIRECTION TEST

This test was intended to examine how well the pilot recognizes directions indicated by the sidestick. This was done by generating a tick every 2 seconds with random direction, strength and pullback. Immediately after a tick, the pilot has the task of deflecting the sidestick in the same direction. A run ends after 2 minutes.

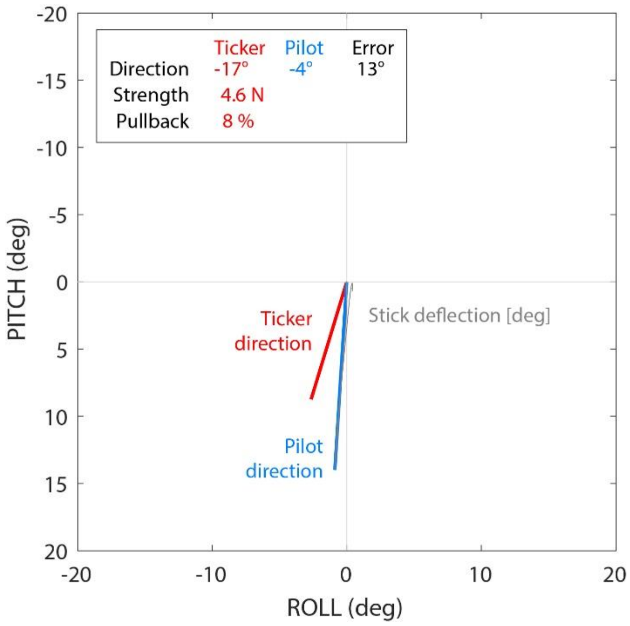

FIGURE 6: Example of a single tick, with the pilot's indication of the recognized direction and the error in between. The axis represents a top down view on the sidestick.

FIGURE 6 shows an example of a single tick with a random direction and with the subsequent sidestick deflection of the pilot. The error between the two directions is 13°. These errors are then plotted over their associated ticker strength and pullback value in FIGURE 7. In cases in which the pilot did not deflect the sidestick, this was assessed as a misclassification and the error was set to 180°. In addition to the data points, box plots give an overview for the respective strength ranges.
In FIGURE 7 it can be seen how the errors become very large for small ticker strengths, below 3 N. Also, in the range 3 to 6 N there are already some misclassifications.

The top 6 outliers for ticker strengths over 4 N have been recognized incorrectly to a critical extent and are therefore particularly interesting. It is important that 3 of these 6 fail classifications have a very high pullback value. Such high pullback values can lead to the direction being confused.

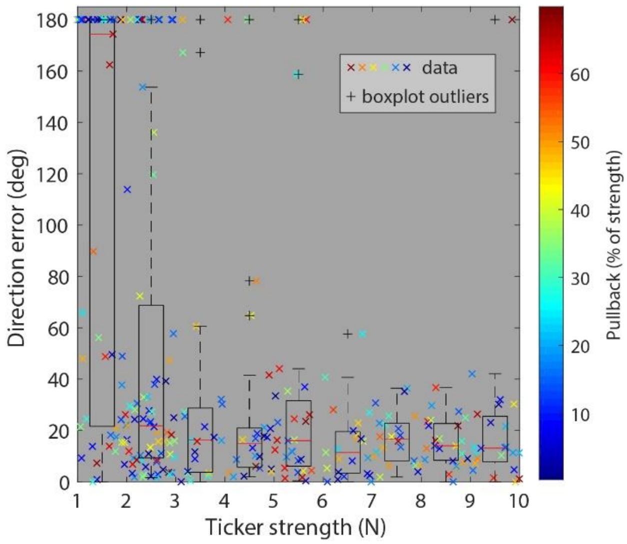

FIGURE 7: Error in direction perception of the ticker for different ticker strengths and pullbacks.

This results in a failure rate of around 2% for reasonable ticker settings, with a strength > 4N and a pullback < 50%. In retrospect, additional data would also be of interest here in order to have more fail data. These can presumably also be recorded with non-pilots. Apart from the three outliers mentioned in the upper right area, the discernible influence of the pullback is rather small.

Without the outliers on top and for strengths above 4 N, the mean direction error is about 15° and the standard deviation is about 11°.

Methodically, this experiment was carried out without a real flight task and without additional workload. The pilots had to hover at any safe altitude, but with an automated controller, which stabilizes the hover on its own. Therefore, the pilots could focus purely on the task. Furthermore, they knew that the next moment a tick is coming. In a real operation, however, the pilot would have awareness of his current situation, which could help him to recognize the direction of an indicated obstacle. In addition, there would be several consecutive ticks instead of a single one. Testing the ticker in a more realistic scenario is the subject of the next experiment.

8. SYSTEM TEST WITH MOVING OBSTACLES

This experiment is a system and stress test with moving obstacles. As previously explained, the ticker is primarily intended to warn of unnoticed obstacles. However, collisions with unnoticed obstacles occur extremely rarely in realistic scenarios, since everything possible is done to prevent these situations. Therefore, moving obstacles are used here to force potential collisions. At the same time, the equivalent situation in which the helicopter is drifting unnoticed towards an obstacle is also covered.

The moving obstacle is created by the experimenter at the push of a button without the pilot noticing. The direction of the obstacle is random. It is placed in the green hazard area and it moves towards the helicopter at a speed of 0.5 m/s. However, the obstacle does not chase the helicopter. Instead, the obstacle flies to where the helicopter was when the button was pressed. A collision would therefore not always occur because the helicopter could unintentionally drift away. Only one moving obstacle is active. The obstacles are invisible so that the pilot's reaction is based on the haptic cues. In order to avoid conflicting information, the obstacles are more likely to arise on the sides or from behind. In addition, a strong brownout is used, which also restricts the view onto obstacles. To expand this experiment in the future, drones could be used as an obstacle to provide additional visual cues.

The scenario was flown in a forest clearing (with a diameter of 5 rotor diameters) with attitude command (AC), strong brownout and strong turbulence. The pilots had the task of hovering 5 m above the ground with a safe distance from all obstacles, and if necessary to evade and stabilize again. Climbing out of the forest clearing was only allowed in an emergency, because there was an imaginary danger that the helicopter would be shot at. Overall, the workload was high, to the extent that the pilots found it often difficult to stabilize the hover at all. The exaggerated turbulence forced constant pilot inputs and the brownout made visibility extremely poor and sometimes completely removed it for a short time (but only for less than 3 seconds).

The experiment was divided into three parts, (1) only forest clearing obstacles, (2) only moving obstacles and (3) both forest clearing and moving obstacles. In the first part, the pilots were able to familiarize themselves with the ticker and play around with it freely for 15 minutes. With the moving obstacles in the other parts, the pilots ideally had to evade and then stabilize the helicopter again into hover. This sequence of hover, moving obstacle, evade, stabilize and hover again was repeated about 50 times with a pilot. At the third part, the pilots often found themselves in a situation where the moving obstacle forced an evasion to the trees. But then the trees got indicated by the ticker, which resulted in rapid changes of the directional cue.
The pilots knew in this experiment that an obstacle could approach, so the surprise effect was minimal. The exact point in time, the direction and the trajectory of the obstacle, however, were unclear. Since the surprise effect is very strong in reality, it would be interesting to also investigate this in the future.

As a result, the pilots knew the direction of the obstacle 95% of the time when only the moving obstacle was present. If there were additional obstacles from the forest clearing, the direction was known in 85% of the cases. These numbers come from the data, but also correspond to the pilot survey. However, if the direction was unclear, the pilots evaded upwards. Therefore, it has come to a collision in less than 4% of cases. Without the ticker on the other hand, it would have come to a collision in about 85% of cases.

The ticker was rated as very intuitive with almost no training required. Most often, confusion arose when several obstacles from opposite directions became critical. In almost all cases in which the pilots said while flying that they are currently not sure where the obstacle is, they still steered away from the obstacles intuitively. However, in a final system there should be a visual display where the pilots can double check their haptic impressions.

Overall, the feedback from the pilots was very positive, for example: "This is the best haptic feedback I have ever tested." All five pilots said they would use such a system.

Finally, the pilots were asked to extrapolate the ticker onto real situations based on their operational experience: "How many accidents of this kind could be prevented with this ticker." Here, "this kind" means perfect obstacle data is available, the drift speed is low and excluding vertical collision. First of all, everyone said it was difficult to answer. But, the reduction of accidents is ultimately the goal of the ticker and therefore the most important measure for evaluation. It is therefore a good idea to carry out estimates, and who is better suited to do this than the pilots themselves. However, as result all five pilots independently estimated 75% of these collisions could be prevented with this ticker.

9. CONCLUSION AND OUTLOOK

The ticker is implemented with force pulses on a sidestick to warn against unnoticed obstacles in order to reduce the risk of collisions. The current hazard area (green, orange, red) are indicated by activating the ticker and through different frequencies. Due to the ticker, the pilots always knew which hazard area they were in during the experiments.

The ticker is annoying and worsens the handling qualities in the hover task from satisfactory to adequate. In normal operation, the function is therefore not active, but only in an emergency as a hazard warning, but not as a main input to control the distance. As a warning cue the ticker was evaluated as non-disturbing. A regression model was determined for the handling quality rating of the pilots at the hover task. It sums up the result and allows predictions for different settings of the ticker.

The sidestick deflection on its pitch and roll axis indicates the direction away from the most dangerous obstacle. The influence of the ticker strength (and pullback) on the quality of direction recognition was determined experimentally. If the tick impulse is less than 3 N · 35 ms, the misclassification rates became extremely high. A useful range for the tick impulse is thus something from 4 N · 35 ms to 7 N · 35 ms, whereby the upper limit is determined by the disturbance. Above 4 N almost all errors were below 50° and the fail rate was 2%. The mean directional error for the correctly classified was 15° with a standard deviation of 11°.

The method of using moving obstacles to force collisions and thus test the ticker has been proven in this study. Of around 200 collisions that would have happened without the ticker, only 8 actually happened in the simulator experiment. The pilots rated the ticker as very intuitive and almost no training was necessary. Furthermore, all pilots rated the current warning que design as not disruptive. They would all use it and also recommend it to other pilots.

The pilots also noted that an additional visual display could be helpful for them, to double check their haptic impression. A visual display of the ticker with a head-worn display, however, is the subject of further work. This also includes a 3D audio display and investigations into how these systems work together and what advantages different multimodal combinations have.

Many of the studies presented here are of a fundamental nature, so that further work can be based on them. One example is comparative studies with other definitions of the hazard area, such as time-to-collision or risk values. A closer look at full 3D movement with vertical collisions in combination with the ticker is also part of further works.

The ticker settings determined here can vary slightly with other sidestick models, because the impulse inputs mean that the stick's short-term reactions are particularly important.

To sum it up, with the last question of the pilot survey, all five pilots independently estimated 75% of accidents of this kind could be prevented with this ticker.

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