# ONERA-DLR JOINT RESEARCH ON TACTILE CUEING FOR REACTIVE OBSTACLE AVOIDANCE DEDICATED TO LOW SPEED HELICOPTER MANEUVERS

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**Abstract**

In the framework of their long-term cooperation in the field of rotorcraft research and technology, DLR and ONERA are sharing their complementary activities in the area of tactile cueing with active sidesticks for obstacle avoidance in the low speed flight speed domain for helicopters. The purpose of the haptic feedback is to provide the pilot with assistance regarding the avoidance of the obstacles in the vicinity of the helicopter, which could either be overlooked because of degraded visual environment or due to high workload: although being fully aware of their existence, some highly stressful and/or demanding piloting situations can lead to a wrong appreciation of the relative distances between the helicopter elements (in particular for configurations where the pilot can hardly see the rotor blades) and the surrounding buildings, cliffs, walls, etc. A joint-team collected requirements and defined plausible use-cases for later evaluation in piloted simulation. Each partner developed a function with the objective to calculate and provide efficient haptic feedback through active sidesticks for the piloting task of a helicopter. The paper will gather and present the different approaches, algorithms and cueing forces used. The first of qualitative pilot assessment will be presented.

Modern helicopters are complex and versatile aerial systems, able to perform a wide variety of missions (transport, tactical, SAR[†],...) in many different environments. Although the recent technological developments have largely contributed to an overall increase of safety, incidents or accidents still remain present, in particular when flying in difficult conditions such as uncertain environments or adverse weather, coupled with demanding, high-workload tasks from the pilot (*e.g.* hoisting).

For this reason, many risk-avoiding systems have been implemented as various types of alerts, mainly audio or visual alarms. However it has been shownn that: *i)* usually those type of signals call for some amount of information treatment from the pilot[1] and *ii)* an over-accumulation of alerts can lead to a phenomenon of attentional tunneling,[2] where the pilot stays focused on the "wrong" information and neglects more useful alarms or cues.

With the recent increase in use of FBW[‡] systems, the introduction of the haptic modality through the control inputs appear as a promising solution to avoid some of the drawbacks exposed above.

Previous activities have been led at ONERA — The French Aerospace Lab — on this subject, in particular within the frame of AZUR (*Autonomy in Urban Zone*) research project,[4] for which one of the objectives was to calculate and provide efficient haptic feedback through active (motorized) sidesticks for the piloting task of a rotary wing (RW) aircraft, in the vicinity of visible and known obstacles of various types. Developments and evaluations were done in simulation using a 10-ton class helicopter model, through an UAV obstacle field navigation benchmark proposed by U.S. Army[5] and used in the other activities of the AZUR project. The sizes and distances between obstacles

[†]Search And Rescue

[‡]Fly-By-Wire

were adapted to a helicopter with a 16 m rotor diameter. Furthermore, additional obstacle sets have been added, corresponding to a very simple urban environment. Both sets of obstacles (UAV-oriented benchmark and urban buildings) correspond to different flying scenarios and operations: the first one is more suited to evaluate emergency avoidance maneuvers (particularly in the case of DVE[†]), whereas the second one is adapted to low-speed/hovering situations.

During this project, the integration of rotorcraft flight model and obstacle map was done on PycsHel, the prototyping and real-time piloted simulation environment at ONERA Salon de Provence Research Facility. Two different logics have been used in order to generate force feedbacks on the cyclic active sidestick (no feedback was applied to the collective axis): the first one is based on force gradients surrounding obstacles, whereas the other one is partially based on $\tau$-theory.[6] More than 170 simulation runs have been performed in order to evaluate the benefits of using haptic feedback for obstacle avoidance.[7] It has been concluded that depending on the task performed, the force feedback logics used should be different. For emergency and/or high speed avoidance maneuvers, the $\tau$-based geometric approach gives good results, providing tactile cues at a well suited distance from the obstacle (mainly on the lateral cyclic control input). For multiple/close obstacles and low helicopter speeds, the virtual force-field approach is more suitable. Since the force bias is sent on both lateral and longitudinal cyclic control axes, it helps the pilot to "feel" the proximity of obstacles located behind the helicopter, or outside his field of view.

At DLR — German Aeronautics and Space Research Center — the haptic obstacle avoidance was part of a the cooperative project SiRaSKoF-H. In the current HOTAS cooperation project, ONERA and DLR share their complementary activities regarding Haptic Obstacle and Terrain Avoidance Systems.[8] Each partner developed an approach how to detect and calculate cueing forces from the obstacle scenery and evaluated different tactile cues. The different approaches and their qualitative evaluations are presented in the following and common conclusions are drawn.

HOTAS is the continuation of a long lasting cooperation between ONERA and DLR in the field of tactile cueing. In a former project ONERA and DLR cooperated successfully in the evaluation of the benefits of haptic feedback for vortex-ring-state (VRS) protection.[9,10] The function used a VRS prediction model developed by the ONERA, capable of predicting the actual closeness to the VRS onset during flight. DLR developed a tactile cueing function on the collective based on a softstop. This function was tested in DLRs ground simulator and on the Flying Helicopter Simulator (FHS). Workload ratings performed showed clear reductions with the cueing function and the pilots commented positively on the function.

[†]Degraded Visual Environment.

# 1 ONERA APPROACH

The Systems Control and Flight Dynamics Department at ONERA developed an assistance solution based on a virtual sensor for the obstacle detection coupled with a 2-axis motorized sidestick used as cyclic controller. In this section, the overview of the method, the simulation environment PycsHel and the results of the evaluation campaign are successively presented.

## 1.1 Obstacle detection

All frames are supposed orthonormal, direct-oriented:

- $\mathcal{R}_0 = (O_0, \vec{x}_0, \vec{y}_0, \vec{z}_0)$: Earth-defined reference inertial frame, attached to the ground. $O_0$ is the center of the map, $\vec{x}_0$ points towards north, $\vec{y}_0$ towards east and $\vec{z}_0 = \vec{x}_0 \wedge \vec{y}_0$ towards the center of the Earth;
- $\mathcal{R}_a = (O_a, \vec{x}_a, \vec{y}_a, \vec{z}_a)$: aerodynamical frame, defined by the helicopter air speed $\vec{V}$. $O_a$ is the center of the airframe, $\vec{x}_a$ points along $\vec{V}$ ($\vec{x}_a = \vec{V}/||\vec{V}||$), $\vec{y}_a$ is orthogonal to $\vec{x}_a$ and towards the right (from a pilot point of view), and $\vec{z}_a$ downwards (note: frame is undefined if $\vec{V} = \vec{0}$);
- $\mathcal{R}_b = (O_b, \vec{x}_b, \vec{y}_b, \vec{z}_b)$: aircraft body frame, attached to the airframe. $O_b$ is the center of the airframe, $\vec{x}_b$ points from aft to nose, $\vec{y}_b$ is orthogonal to $\vec{x}_b$ and towards the right (from a pilot point of view), and $\vec{z}_b$ downwards.

$\left(\vec{U}\right)_{\mathcal{R}_n} = \begin{pmatrix} \vec{U}.\vec{x}_n \\ \vec{U}.\vec{y}_n \\ \vec{U}.\vec{z}_n \end{pmatrix}$ are the coordinates of array $\vec{U}$ in frame $\mathcal{R}_n$, and $\mathbf{M}_{ab}$ is the rotation matrix between frames $\mathcal{R}_a$ and $\mathcal{R}_b$, such as:

$$\left(\vec{U}\right)_{\mathcal{R}_a} = \mathbf{M}_{ab}.\left(\vec{U}\right)_{\mathcal{R}_b} \tag{1}$$

A Virtual Distance Sensor (VDS) is defined as an array originating from $O_b$ and intersecting in a point $M$ the closest facet of the simulation (virtual) world. The orientation of the VDS is defined by the unit vector $\vec{T} = \overrightarrow{O_bM}/||\overrightarrow{O_bM}||$.

The components of $\vec{T}$ in the Earth reference frame can be piloted through the simulation environment, which allows as well to get back the intersection coordinates $M$ in real-time. As a consequence, a moving set of one or more VDS will be used as a basis for the obstacle detection method used in this study. Similar to a LiDAR sensor, the VDS will be scanning the surroundings of the helicopter by continouously rotating around a vertical axis, moving with the aircraft.

In this approach, the rotation plane of the obstacle detectors is chosen to be constantly horizontal (but moving with the helicopter mass center), in order to compensate for the attitude angles of the fuselage: $\vec{T} \wedge \vec{Z}_0 = 0$. As a consequence, the coordinates of the direction array in Earth frame can be expressed as:

$$\left(\vec{T}\right)_{\mathcal{R}_0} = \begin{pmatrix} \cos\Psi \\ \sin\Psi \\ 0 \end{pmatrix} \tag{2}$$

The rotation speed $\Omega$ of the VDS is supposed to be constant, thus azimuth angle $\Psi$ can be expressed as:

$$\Psi(t) = \Omega t \tag{3}$$

Let us denote $D = ||\overrightarrow{O_b M}||$. $D(\Psi)$ is the distance returned by the VDS at current azimuth $\Psi(t)$ (see Figure 1). In order to characterize the distance and position of the closest obstacle, the minimum value of $D$ over a 1-rev. period is computed:

$$\Psi^* = \underset{t \in [t_i; t_i + 2\pi/\Omega[}{\arg\min} D(\Psi) \tag{4}$$

$$D^* = D(\Psi^*) \tag{5}$$

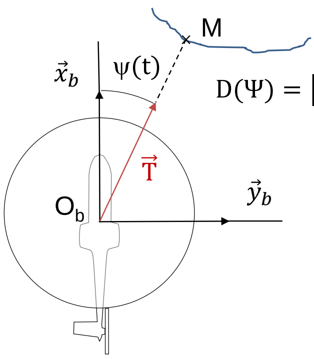



Figure 1: Top view of the obstacle scanning through Virtual Distance Sensor.

Furthermore, in order to increase the temporal resolution of the scanning, a set of $n \geq 1$ VDS equally distributed in azimuth can also be used, so that eq. (3) becomes for the $k$-th VDS:

$$\Psi_k(t) = \Omega t + \frac{2k\pi}{n} \quad 0 \leq k \leq n-1 \tag{6}$$

and the closest obstacle is then found as:

$$\Psi_k^* = \underset{t \in [t_i; t_i + 2\pi/(n\Omega)[}{\arg\min} D(\Psi_k) \tag{7}$$

However, the information of the distance alone might not be fully sufficient in order to characterize a risk of collision: the proximity of an obstacle could also be defined as temporal proximity, *e.g.* an obstacle far away could be potentially dangerous if the aircraft velocity is high enough. For this reason, another criterium could be used in addition to $D^*$: let $\vec{V}$ be the velocity of the helicopter w.r.t. Earth frame. The time-to-contact $\tau^*$ is defined as the ratio of the distance to the closest obstacle $D^*$ over the projection of $\vec{V}$ along the direction of $M$:

$$\tau^* = \frac{D^*}{\vec{V}.\vec{T}} \tag{8}$$

Of course, the time-to-contact information is only useful when the velocity is nonzero, otherwise the distance information becomes pertinent again.

## 1.2 Force feedback implementation

Once the distance/time-to-contact value has been obtained, it is necessary to convert it into a useful information for the pilot in terms of flight safety, through the motion of the haptic interface sidestick.[11]

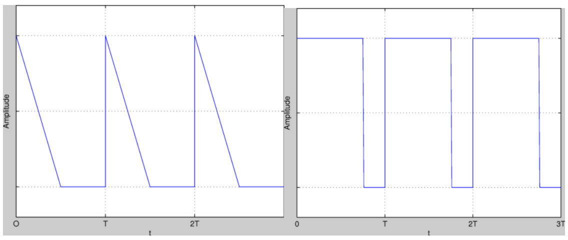
In a first approach, it can seem pertinent to transform the continuous domain $(D^*, \Psi^*) \in \mathbb{R}^{+2}$ into an also continuous subset of the sidestick variable space, such as translation motion or vibration frequency. However after various preparatory simulations performed with test pilots, it appeared that making the parameters of the stick vary at the same rate than the obstacle detection criteria was not very helpful for the pilot, because he has to monitor continuously the relative evolution over time of these parameters (*e.g.* is the frequency/amplitude currently increasing, or diminishing ?), which is sometimes hard to perform, in particular in the case of slow maneuvers.

To avoid this effect, two different strategies for haptic feedback have been designed: Direct and Indirect Haptic Assistance.

### 1.2.1 Direct feedback impulsions

In this case, and to avoid any extra need of analysis from the pilot as mentioned above, a safety classification consisting of only 3 different situations has been designed:

- Mode 0 "*None*": the pilot is far enough from any obstacle, nothing to report.
- Mode 1 "*Alert*": the pilot is close to the obstacle and has to be informed about it, however it is still considered safe enough to operate for a sustained period of time in these conditions.




(a) Alert cueing (b) Avoid cueing

Figure 2: Haptic feedback cues in the case of obstacle proximity.

- Mode 2 "*Avoid*": the pilot is too close to the obstacle, and the situation is considered dangerous: the pilot must immediately get away from the obstacle to ensure his safety.

The proposed corresponding cueing scheme to translate these different conditions into active stick actions is as follows:

- *Alert* cue: the control cyclic stick is moving gently with regular, constantly spaced "ticks" displacements. The shape of the signal is a dissymmetrical sawtooth-like waveform (see Figure 2a), in order to give the pilot an information about the direction of the obstacle: the steepest (*i.e.* shortest) side of the motion will be associated with an indication to stay back from the corresponding direction, whereas the slowest descent is the return to the resting position of the sidestick.

- *Avoid* cue: the stick is moving with greater amplitude and slower frequency through a succession of rectangular steps (see Figure 2b), meaning a stronger urge to follow the direction in which the stick is moving.

In the present approach, those controlled displacements are modelized as extra forces applied by the sidestick actuation to both direction axes. Let $F_{\text{lon}}$ (resp. $F_{\text{lat}}$) be the force applied to the longitudinal (resp. lateral) cyclic control stick axis. First, the direction of the current closest obstacle is projected into the helicopter body frame:

$$\left(\vec{T}^*\right)_{\mathcal{R}_b} = \mathbf{M}_{b0} \cdot \left(\vec{T}^*\right)_{\mathcal{R}_0} \tag{9}$$

After that, $F_{\text{lon}}$ and $F_{\text{lat}}$ are obtained by mapping the generated cue waveform onto the respective directions of $\left(\vec{T}^*\right)_{\mathcal{R}_b}$.

#### 1.2.2 Indirect haptic motion

As an alternative to the previous law, a completely different assistance feedback design has been tested. The basic idea is that a trained pilot or vehicle driver, when confronted with an sudden, unwanted excursion of its control stick or wheel, would instinctively hold it back and even apply a "counter-order" input as a reflex maneuver. This observation led to the proposition of innovative haptic assistance laws,[12] where the stick would be pushed *towards* the obstacle rather than away from it, with the assumption that the pilot would react and quickly move the stick in the opposite direction.

As it has been said earlier, a constant gradient evolution of the force feedback parameter applied to the stick could be hard to apprehend from the pilot. For this reason, a nonlinear force law as a function of the distance has been used, based upon a *logsig* function:

$$|F| = \frac{F_{\text{max}}}{1 + e^{-(\alpha D_{\text{min}} + \beta)}} \tag{10}$$

where $\alpha$ and $\beta$ are tuning parameters. The inflexion of the curve is low at the extremes and stronger in the middle, transitional zone, in order to have a non-monotonic behavior for the pilot (see Figure 3)

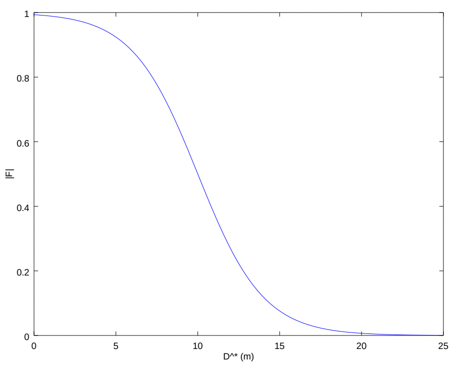



Figure 3: Force feedback profile of the indirect haptic motion.

### 1.3 ONERA simulation environment: PycsHel

The developments and simulations were led through the PycsHel prototyping environment, part of Lab-

Sim simulation facilities at ONERA center of Salon de Provence. The simulator CAVE-like room consists in 2 seats replicating the standard inner disposition of a helicopter cockpit and a 270° horizontal field-of-view display obtained with 3 white vertical walls and 3 videoprojectors mounted on the ceiling, completed with a 4th videoprojector pointing downwards for the bottom view. For classical, non-augmented helicopter simulations, standard (passive) flight controls are available for the cyclic, collective and pedal inputs on the left seat, whereas the right seat features motorized programmable active sidesticks (on cyclic and collective controls), manufactured by WITTENSTEIN.[13] A picture of the simulator cabin is provided in Figure 4.

Figure 4: Overview of PycsHel CAVE cabin.

The visual scenery is generated through a custom-made graphical engine, based on open-source 3D toolkit OpenSceneGraph, and features orthographic height-field based terrain fueled by data proveided by CRIGE†-PACA — the geomatic resource center for region *Provence-Alpes-Côte d'Azur*, South of France. In addition to day/night conditions, procedural realistic weather (clouds, precipitations) can be activated through a graphical library developed by Sundog™ Software.

The simulator architecture relies on Kronos, a real-time DDS-based simulation orchestrator, which allows a dynamic library encapsulation, multiple language connectors and a data-centric architecture. This global environment is able to run in real-time high fidelity aircraft flight dynamics code, such as HOST[14] (Airbus Helicopters). Moreover, and thanks to an entirely open and programmable architecture, a whole variety of dedicated models/functions developed using Matlab/Simulink, C++, FORTRAN, can be integrated and interact with the flight mechanics code.

For this study, the chosen rotorcraft is a 10-ton class cargo helicopter equipped with a Stability Augmentation System (SAS), which is implemented as a proportional feedback on the angular rates $p$, $q$, $r$. The closed-loop eigenvalues of the equivalent linearized dynamics of the helicopter at low speeds are plotted in Fig. 5.

†*Centre Régional de l'Information Géographique*.

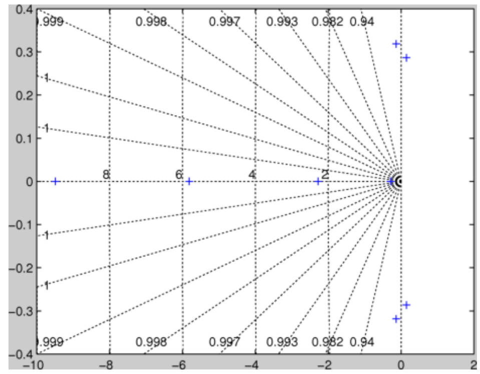


Figure 5: Closed-loop eigenvalues of the helicopter model with the Stability Augmentation.

### 1.3.1 Task 1: hovering near cliff

Two different scenarios were designed in order to evaluate the efficiency of the haptic feedbacks. The first one is based on a rescue-type mission in a mountain zone: a specific, highlighted point on a cliff side is given as reference, and the pilot is instructed to maintain hovering flight during 1 minute at various distances from the cliff: 30m, 10m, 5m, first without haptic feedback, then the same sequence is performed with haptic feedback enabled. For this scenario, entering into Alert or Avoid modes was determined on a distance-based threshold $\underline{D}$ fixed as 20m for Alert, and 4m for Avoid. This scenario took place in the *Massif des Alpilles*, a small range of low mountains located in the French region of Provence.

### 1.3.2 Task 2: entering/exiting confined zones

For the second scenario, three sets of cubic-shaped obstacles were added to the existing terrain database. They represent Confined Zones (CZ), such ones a pilot can encounter when flying in densely urbanized areas, or at the bottom of deep valleys. Each set is comprised of 11 identical cubic blocks arranged in a L-shaped cul-de-sac, with 2 blocks defining a small corridor at the entrance (see Figure 6). The pilot will have to approach at constant slope, decelerate within the zone, turn left, touch down at the bottom of the zone, and then turn around to perform his way back to the entrance of the zone.

Three different sizes have been devised: Large, Medium and Narrow, each one corresponding to a given value of the inner width (wall-to-wall) of the zone. The respective widths, as well as the values of the Alert and Avoid thresholds, are summarized in Table 1.

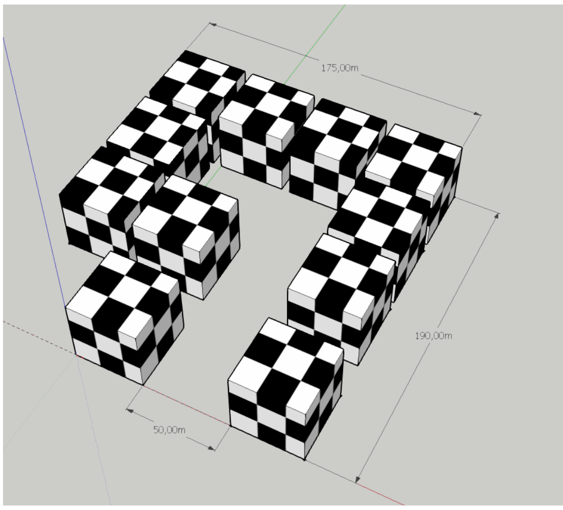



Figure 6: 3D isometric view of the Medium Confined Zone.

| | Width | $D_{\text{alert}}$ | $D_{\text{avoid}}$ |
|---|---|---|---|
| LCZ | 70.0 | 20.0 | 4.0 |
| MCZ | 50.0 | 12.5 | 2.5 |
| NCZ | 30.0 | 5.0 | 1.0 |

Table 1: Parameters for the Confined Zones sets (all values in m).

## 1.4 Experimental campaign

### 1.4.1 Experimental protocol and evaluation criteria

A panel of 6 pilots was asked to perform both tasks in the PycsHel simulation environment. All of them were confirmed helicopter test pilots from DGA-EV[†] and EPNER[‡], with a significant number of flight hours.

After a certain period of familiarization with the simulator environment and the flight dynamics of the helicopter + SAS (with no prescribed duration), each pilot was asked to perform the tasks once for every parameter value (distance to cliff for task 1, size of the zone for task 2), with and without sidestick active feedback.

Evaluation was done using the NASA Task Load index or TLX,[15] a multi-dimensional rating procedure that provides an overall workload score based on a weighted average of ratings on six subscales: Mental Demands, Physical Demands, Temporal Demands, Own Performance, Effort and Frustration, each one to be rated on a 20-value scale between Perfect/Very low/Good and Failure/Very high/Poor (according to the context). The degree to which each of the six factors contribute to the workload of the specific task to be evaluated from the raters' perspectives is determined by their responses to pair-wise comparisons among the six factors; *e.g.* Performance *vs.* Physical Demand, Mental Demand *vs.* Temporal Demand, etc. Ratings of factors deemed most important in creating the workload of the task are given more weight in computing the overall workload score, thereby enhancing the sensitivity of the scale.

In addition to those six criteria originally present in the NASA TLX evaluation procedure, two extra criteria have been added for this experiment: Situational awareness and Safety. Magnitude ratings on each subscale are asked after each performance of a task or task segment, in order to get an immediate return on the pilot experience.

During the first part of the evaluations and open discussions with the pilots, it appeared at a very early stage that the indirect haptic motion assistance mode developed in §1.2.2 was repeatedly given a very low rating by all pilots, whichever task they were performing. Their appreciations were strongly unfavourable to a system which would attract the helicopter closer to the dangerous zone, in particular during missions where the baseline workload would already be important such as hoisting. In order to make better use of the "counter-order" reaction principle behind this approach, more work would be necessary to adapt it to aircraft piloting situations.

Similarly, the use of an Alert/Avoid criterion based on a time to contact information $\tau^*$ as expressed in (8) seemed not very intuitive for the pilots for low-speed or hovering tasks, because in these situations they more or less expect an information regarding the actual distance to the closest wall.

As a consequence, only the direct impulsions (§1.2.1) based on a distance measurement $D^*$ have been used as haptic feedback during the actual experimental campaign. In the presentation of results, the following abbreviations might be used to denote the given subtasks: for task 1 the distance in meters at which the pilot is instructed to maintain hover, followed by NF (No Feedback) or AF (Active Feedback) whether the haptic feedback assistance function is turned off or on:[†] and for task 2 the type of Confined Zone (Large, Medium, Narrow), also followed by NF or AF: examples 30/NF, NCZ/AF.

### 1.4.2 Results and analysis

In order to test the global effect of the haptic feedback on the workload, a Wilcoxon matched-pairs signed-rank test[16] is performed for the different subtasks.

[†]Flight testing unit of the French Defense procurement and technology agency (DGA).

[‡]French test pilot school.

[†]This off/on setting only corresponds to the global state of the assistance function, and not to the actual presence of a force feedback: when it is on, the existence of the impulsions still depends on the activation criterion based on the distance to the closest obstacle.

| Task 1 | | | Task 2 | | |
|---|---|---|---|---|---|
| 30m | 10m | 5m | LCZ | MCZ | NCZ |
| 1.0 | 0.406 | 0.031 | 0.812 | 0.062 | 1.0 |

Table 2: $p$-values for the Wilcoxon signed-rank test performed on the different subtasks.

This test is used to define whether the median difference between pairs of observations (in this case workload with NF and workload with AF) is zero. Contrary to the classical Student t-test, the Wilcoxon signed-rank test does not rely on the hypothesis of a normal distribution of the differences.[17] The results of the test (expressed as the $p$-value) are summarized in Table 2.

From these results, we see that the null hypothesis (in this case there is no difference between NF and AF) cannot be rejected within the usual 5% significance level, except for the task 1 at a distance of 5m.

A more in-depth analysis can be performed by looking at the decomposition of the TLX workload: on Figures 7 to 9 are presented the workload value averaged for all pilots performing task 1 (adjusted by excluding the 2 more extremal values), for both NF and AF cases (low values correspond to low workload). A median line showing the frontier between good and bad has also been plotted. Below are some immediate remarks:

- At 30m from the cliff, there should not be any difference between 30/NF and 30/AF, because the feedback is never applied at this distance. However, a decrease of workload is perceived with AF (0.6 *vs.* 0.7), which is probably due to the familiarization to the task.
- At 10m, the perceived workload increases when the feedback is activated (0.82 *vs.* 0.92). All subcriteria are rated within the right part (less good) of the scale in AF. In NF, all sub-criteria are better or equal (for frustration and situational awareness). Globally, the haptic feedback does not improve the situational awareness, and slightly decreases the feeling of safety.
- At 5m, the perceived workload increases when the feedback is activated (0.97 *vs.* 1.09). All subcriteria are rated within the right part (less good) of the scale in AF. In NF, all sub-criteria are better, except for safety. This can be explained by the purpose of the Avoid mode, which will immediately push away the pilots when they are too close to the cliff. This may explain the significance level observed in Table 2. Otherwise and most of the time, the Alert mode is not judged helpful.

The same analysis can be performed for task 2:

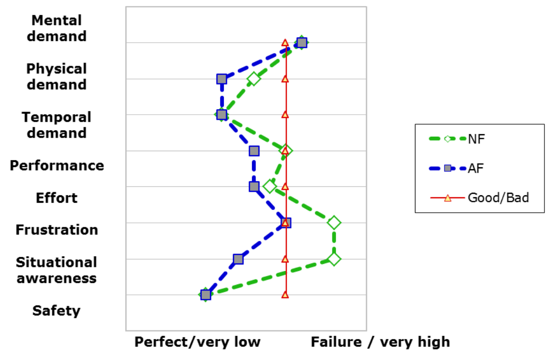



Figure 7: Average TLX evaluation for task 1 (hovering near cliff) at 30m.

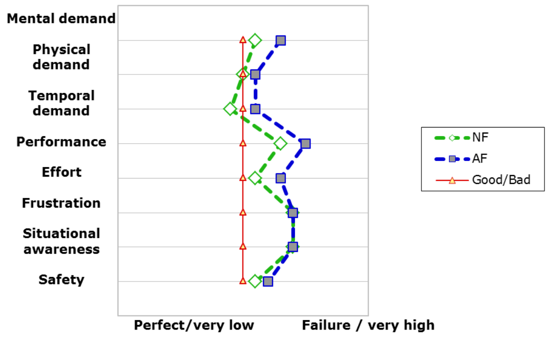



Figure 8: Average TLX evaluation for task 1 (hovering near cliff) at 10m.

- For the LCZ, the workload is on the left side of the median line for both NF and AF. Workload is lower with AF, however the difference is rather small (0.51 *vs.* 0.56), but all subcriteria are rated better or equal (for physical demand).
- For the MCZ, the workload is mainly on the left side of the median line for NF and AF, except for mental demand and effort: the task appears to get more difficult. With AF, workload is lower or equal (for mental & temporal demand), but here again the mean difference is small (0.6 *vs.* 0.68). Average workload is higher than in the previous case (LCZ).
- For the NCZ, the results are more spread around the median line, with a bit more subcriteria on the left side (*i.e.* rated as better). The average workload is higher than in MCZ, and is slightly better in AF than NF, but the difference is not significant. Only physical and temporal demand are rated as higher (worse) with AF.

For all cases, safety and situational awareness are rated better with AF.

Moreover, for this task the TLX evaluation as presented above can be completed by another criterion:

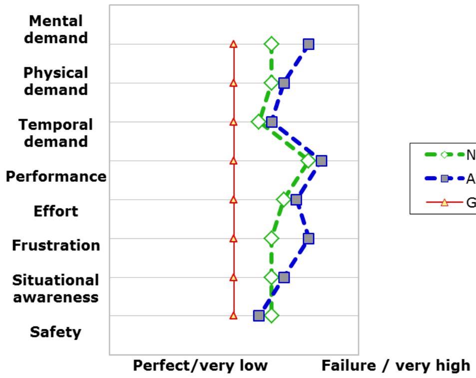



Figure 9: Average TLX evaluation for task 1 (hovering near cliff) at 5m.

the non-dimensional ratio between the duration spent within Alert or Avoid conditions (*i.e.* $D^* < \underline{D}_{\text{alert}}$ or $\underline{D}_{\text{avoid}}$), and the total duration of the run (from the entrance until the exit of the zone). This criterion can be calculated even if the feedback is not applied, and provides an indication of the risk-taking tendency of the pilot when in "natural" conditions in NF *vs.* when the AF is present. The results (averaged for all pilots) are presented in Table 3.

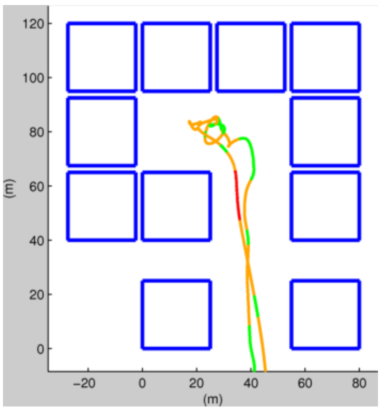



Figure 10: Example of an upper-viewed trajectory within the Medium Confined Zone — green: outside Alert/Avoid domains, orange: Alert, red: Avoid

The results expressed as TLX workload and in Table 3 can be analyzed in a similar way. For example, the difference AF/NF is not very high for both LCZ and NCZ cases. For LCZ, this is due to the fact that the pilots are not exposed very often to the feedback because of the large size of the zone, in which it is not difficult to fly away from the walls. For NCZ, the pilots reported that it was often difficult to perceive the direction of the impulsions, so they did not always immediately know where was the closest obstacle (hence a lack of workload reduction). However in both cases, situational awareness as well as safety were rated as

| | Alert | | Avoid | |
|---|---|---|---|---|
| | w/o HF | w/ HF | w/o HF | w/HF |
| LCZ | 17.7% | 16.7% | 0% | 0% |
| MCZ | 26.5% | 11.9% | 0% | 0% |
| SCZ | 40.6% | 34.7% | 3.2% | 1.4% |

Table 3: Alert and Avoid duration ratios without and with haptic feedback (HF), for the different sizes of Confined Zones.

better with AF. In addition to this, for NCZ the short distance between the blocks (less than 2 rotor diameters) coupled with the visual appearance of the textures at close range (lack of contrast) required high levels of concentration from the pilots, and partially masked the benefits of the haptic feedback. On the other hand, the MCZ appears as an interesting compromise, where the differences NF/AF are much more visible.

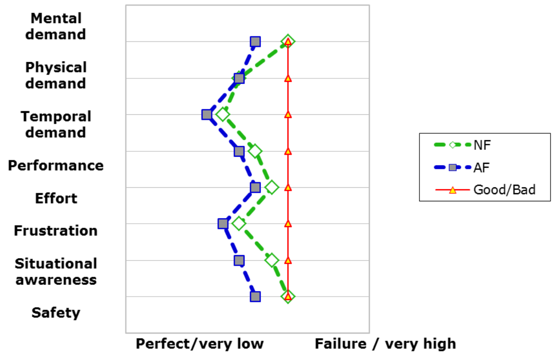



Figure 11: Average TLX evaluation for task 2, Large Confined Zone.

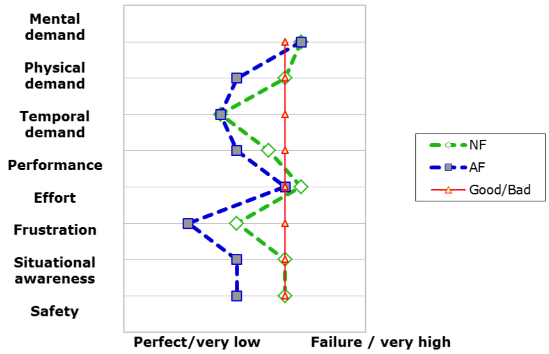



Figure 12: Average TLX evaluation for task 2, Medium Confined Zone.

Subjective assessments made by pilots during comments and discussions were also collected and synthesized. For task 1, the directional information pro-

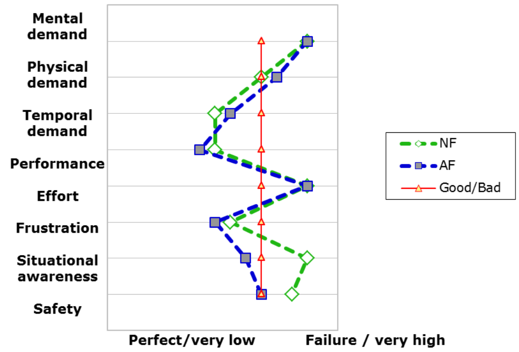



Figure 13: Average TLX evaluation for task 2, Narrow Confined Zone.

vided by sidestick motion (*i.e.* where shall the pilot go to decrease risk) loses its interest since there is only one wall/cliff, and the continuous impulsions can appear as more uncomfortable as fatigue increases. Even if it is possible to pilot transparently through the stick motion, it can interfere with the smallest corrections necessary to maintain a precise hovering point. Some pilots suggested that a smallest amplitude/greater frequence motion such as a vibration could be more adapted to this case.

For task 2, the directional information becomes pertinent again, however it was sometimes difficult to discriminate between the two directions of the motion axis of the stick (*i.e.* between $\Psi^*$ and $\pi - \Psi^*$). Thus, the dissymmetry of the baseline ticking signal shape should be increased.

The Avoid mode was considered useful and well adjusted. For both modes, it would be of course necessary to adapt in flight the threshold values according to the type and size of the obstacle zone (if known or estimated). Furthermore, the idea of a acquit button to temporarily dismiss the Alert mode (while retaining Avoid mode enabled) was also proposed.

Finally, in its actual, proposed implementation, the indirect haptic motion was not accepted at all. Only one pilot estimated that it could generate the appropriate behavior towards escaping the obstacle, but the overall impression was strongly unfavourable.

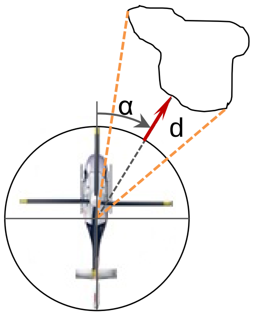
# 2 DLR Approach

DLR implemented a function to provide haptic feedback on the controls for obstacle avoidance. The system was evaluated in the EC135 ACT/FHS simulator cockpit in DLR's Air Vehicle Simulation Center (AVES)[18] by three pilots from German Federal Police with regard to acceptability and preselection of useful tactile cues. A description of the tactile cues which were acting on the active sidestick for cyclic control and the results of the acceptance test are presented in the following to enable a comparison with ONERA's approach. A detailled description of DLR's haptic obstacle avoidance system will be given in a publication at DLRK 2016.[19]

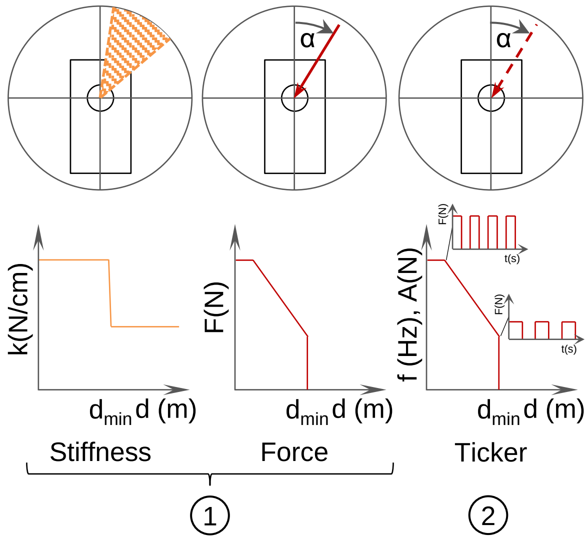
## 2.1 DLR haptic obstacle avoidance

DLR's haptic obstacle avoidance uses obstacle information from a dynamically updated digital three-dimensional terrain model or elevation map as provided by a sensor fusion system in the ACT/FHS. This map is generated by fusioning data of different sensors (LiDAR, RADAR, infrared camera) with a-priori terrain knowledge. Newly detected obstacles are stored in the database and are still known when no longer in sight of the sensors providing a "see-and-remember"-capability. So far only static objects were considered. The sensor integration and development of data fusion system was part of the ALLFlight project (Assisted Low-Level Flight and Landing on Unprepared Landing Sites).[20] The haptic obstacle avoidance is already prepared to use the same digital elevation map, although up to now a static database with preselected objects with a compatible data format was used for system simplification.

The implemented algorithm approximates the distance between the helicopter and the obstacles in the database in an iterative manner fast enough for real-time application. The result is a normalized risk vector between 0 (no risk) and 1 (collision) as was already described by Lam.[21] It points to the closest obstacle or by also taking into account the speed towards the obstacle with shortest time-to-collision. The risk vector is mapped to the four helicopter control axis. So each axis gets its own risk value. This value is further processed in a module for the selection and definition of different tactile cueing patterns to influence the intensity of the haptic feedback. Two different concepts of tactile cueing patterns were prepared for cyclic controls, see also figure 14 for illustration. The first one combines the two tactile cueing elements "force and stiffness". A counter "force" $F$ acts on the stick from the direction $\alpha$ the helicopter sees the obstacle. Additionally the force gradient or spring "stiffness" $k$ is increased for deflections which would command the helicopter towards the obstacle, as was suggested by Lam.[21] Force and stiffness increase when the risk value increases, i.e. the distance $d$ or the time-to-collision decreases according to a nonlinear mapping function. The second concept "ticker" generates rectangular pulses on the cyclic, which direct away from the obstacle. Amplitude $A$ as well as frequency $f$ of the repeating pulse sequence increase with decreasing distance, time-to-collision respectively. The tactile cueing is only active when the distance or time-to-collision is below a predefined minimum distance $d_{min}$.




(a) Helicopter obstacle relation, with *d: shortest distance to obstacle, α: direction of shortest distance*




(b) Tactile cueing concepts acting on cylic stick, with *F: Force, f: Frequency of pulses, A: Amplitude of pulses*

Figure 14: Helicopter obstacle relation and corresponding tactile cueing concepts

## 2.2 Evaluation DLR

End 2014 three EC 135 pilots from German Federal Police evaluated the haptic obstacle avoidance in the AVES simulator. The main objective was to evaluate the general acceptance of a haptic obstacle avoidance for helicopter application, specifically in a civil-flight context, as urban HEMS operation. The second objective was to evaluate two specific tactile cueing concepts "force and stiffness" and "ticker" to identify their intuitivity and usability and identify the relevant parameters for further optimization of the functions. DLR's EC 135 ACT/FHS simulator cockpit in the AVES simulator center served as evaluation platform (figure 15). The cockpit is equipped with an active sidestick from Stirling dynamics for cyclic control and an active sidestick from Liebherr for collective control. A 15 channel projection system provides a field of view of +/-120° horizontally and +35°/-58° vertically.[18] The cockpit was mounted on the motion platform, but motion was not active troughout the experiments. A non-linear EC 135 model with a stability augmentation system (SAS) was used.

Figure 15: EC135 ACT/FHS simulator cockpit in DLR AVES center with active sidesticks

Specifically for the evaluation of a haptic obstacle avoidance in a realistic environment the visual simulator scenario "obstacle city"[22] was designed and implemented in AVES (figure 16). It bases on pilot interviews about relevant scenarios in their daily HEMS experience. An area of 1000 m x 1000 m combines different obstacles arranged as a city surrounded by a rural environent. Amongst these are for example confined areas for possible landings on an urban intersection which is surrounded by multistore buildings, a helipad on a hospital or a forrest-clearing. The whole "obstacle city" is replenished by easy overlooked obstacles like traffic lights, cranes with cable, wind turbines, powerlines and trees.

The pilot's task was mainly to manoeuvre freely, but they were also asked to perform specific manoeuvres to experience the different aspects of the haptic obstacle avoidance. One of the tasks was to purposely approach house walls and traffic lights and observe the systems behaviour. Before the evaluation and after each sortie pilots filled-in a questionnaire addressing various aspects regarding acceptability of the demonstrated functions in particular and the application of tactile cueing for obstacle avoidance in general.

## 2.3 Results DLR

Before the test pilots were asked two central questions with regard to a fictitious ready developed system in a future helicopter. First they could answer their expectation in usefulness "Do you expect that active inceptors can assist pilots at avoiding collisions with obstacles?" on a six point scale ranging from "I am skeptical" to "I am convinced". Second they could state their desire "Do you desire forces acting on the controls, which warn about collisions with obstacles?", from "non desirable" to "desirable". All pilots remarked

(a) Total view top down

(b) Detail: Simulator screenshot of intersection

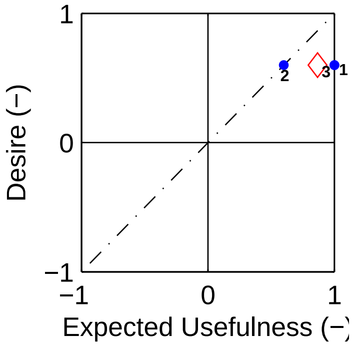
Figure 16: Obstacle City[22]

high expectations for both, usefulness and desire, see figure 17a. At the end of the evaluation pilots were asked the same questions again. The answers were similar (figure 17b). Thus a high acceptance can be stated, although the function was still in a prototype state and not finally tuned regarding the force-feel of the tactile cues.

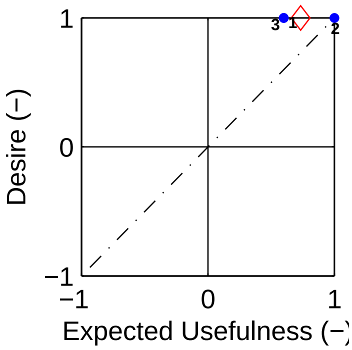
The van der Laan acceptance scale[23] (figure 18) was used to ask indirectly how useful the pilots evaluated each of the demonstrated concepts and how satisfying it was. The scale consists of nine Likert items, i.e. opposing word pairs with a six point ordinal scale*. The pilots were asked to tick that box on each line, which answered best the question: "How would you evaluate the concept for a haptic obstacle avoidance?" for each of the two concepts. The value for usefulness is calculated by forming the average of all odd items (1,3,5,7,9) and the satisfying value is the average of all even items (2,4,6,8). The results of all pilots are shown in figure 19 (a) for the "force and stiffness"-concept and in figure 19 (b) for the "ticker"-concept. They were normalized for the scales ranging from -1 to 1, i.e. "not satisfying/useful" to "satisfying/useful". As can be clearly seen appraisal was high for the "ticker"- and only neutral for the "force and stiffness"-concept.

Furthermore the following observations and comments were made in the pilot interviews. The concept "force and stiffness" was evaluated neutral. It was not evaluated as intuitive. The increased stiffness could only be noticed when the stick deflection substantially increased. One pilot even rated it as annoying. He explained that the permanent control forces were restraining and could be interpreted as stick-jam. But with some experience [i.e. training] it would be easier for him to trust the system. The concept "ticker" was evaluated as intutive and preferable by all pilots. All pilots could recognize the direction of the cue, but

*Originally the van der Laan scale is an odd five point scale. Here an even number of six points was used as it does not provide a centre or possibility for a neutral answer. So the pilots were forced to actively decide for one side when they tended to a neutral answer.




(a) before

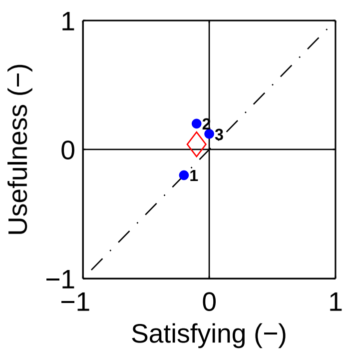



(b) after

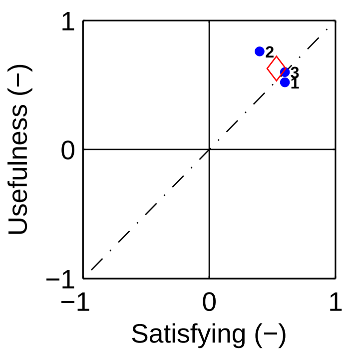
Figure 17: Pilot's "expected usefulness" of and "desire" for a haptic obstacle avoidance in a regular helicopter before and after simulator evaluation (numbered dots) and medium (red diamond); normalized scales -1: "am skeptical/not desirable" to 1 "am convinced/desirable".

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Useful | | | | | | | | Useless |
| 2 | Pleasant | | | | | | | | Unpleasent |
| 3 | Bad | | | | | | | | Good |
| 4 | Nice | | | | | | | | Annoying |
| 5 | Effective | | | | | | | | Superfluous |
| 6 | Irritating | | | | | | | | Likeable |
| 7 | Assisting | | | | | | | | Worthless |
| 8 | Undesirable | | | | | | | | Desirable |
| 9 | Raising Alertness | | | | | | | | Sleep-inducing |

Figure 18: van der Laan acceptance scale[23]




(a) “Force and Stiffness”




(b) “Ticker”

Figure 19: van der Laan acceptance results for both prototypes and for each pilot (numbered dots) and medium (red diamond) on normalized scales ranging from -1 to 1.

not every pilot could recognize the orientation. That means it was not clear if the obstacle was front-right or back-left. One pilot stated that he concluded the direction from his knowledge about the direction of motion of the helicopter: “When I move to the left, than it can only be on the left”. It was assumed that the equal pulse-to-pause ratio of the pulse-pattern lead to the confusion about the intended direction. In this case the time the pulse was active was equivalent to the time it was off. This can lead to misperception when the stick is deflected from trim and pilot forces are non-zero. The pilot does no longer know, when the pulse is on and when it is off. First tests with modified pulse-to-pause ratios, where the pulse is shorter than the pause, were promising.

# 3 CONCLUSIONS

Two different approaches for a haptic obstacle avoidance system were developed at ONERA and DLR. ONERA’s system uses sensor information directly to estimate the distance between helicopter and obstacle, whereas DLR’s system is using an elevation database which is dynamically updated from sensor information. Both approaches calculate haptic cues, which change their intensity with decreasing distance or predicted time-to-collision. Amongst the evaluated forms were continuous forces and repetitive “ticks” with different shapes, frequencies and amplitudes. It can be concluded that a haptic obstacle avoidance through forces on the cyclic stick is expected to be accepted by pilots in regular helicopter, if tuned correctly and after a certain familiarization. Relevant parameters for future system optimization with regard to fulfill the given objectives: “Increase pilot’s situation awareness and assist to avoid collision with obstacles without disturbing helicopter control” are:

- Shape: Another parameter which should be systematically analyzed is the shape of the pulse. DLR only used rectangular pulse-shapes, whereas ONERA also used sawtooth-shapes. Together with the pulse-to-pause ratio the shape seems to be key for an intuitive understanding of the intended orientation of the tactile cue.

- Frequency and Amplitude: The pulses should be resolveable by the pilot, so the amplitude must be substantially high and the frequency must be as low as the pilot can still understand the orientation. This includes physiological restrictions of the human pilot but also the ability of the active inceptor to correctly present the intended tactile cues. Also Eigen frequencies of the helicopter must be avoided and pulses should not provoke stick deflections which lead to dangerous changes of the helicopter flight state.

- Controller Type: Autopilot upper modes change the way the helicopter responds to the controls. It can be assumed that different upper modes need different tactile cues.

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