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# Arbitration of tactile cueing functions for active inceptors systems

Development and test of a software module prioritizing haptic feedback on helicopters sidesticks

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# Abstract

Active inceptors introduce the possibility to provide the pilot with variable tactile feedback and haptic cues during flight, offering an opportunity for improved situational awareness. Specifically, the task of managing several different tactile cues for active sidesticks systems is herein addressed, with the development of a cue arbitrating module.

Firstly, an overview on the context in which these devices operate is assessed. The system is characterized by investigating on evolution, current state of the art and future potential. Afterwards, the problem of simultaneous and conflicting tactile cues is approached, describing the prioritizing module, intended to be used within a helicopter's flight simulator framework. Particularly, this routine aims to handle and filter cueing inputs used for envelope protection purposes. Hence, the program's test and validation process is reported, describing simulated flight sessions and evaluating main remarks. Conclusive considerations for potential future evolution of the system are finally proposed.

# Contents

# List of Acronyms

**AIS** Active Inceptors System.

**CPU** Central Processing Unit.

**e–VTOL** electric, Vertical Take-Off and Landing.
**EHA** Electro-Hydraulic Actuator.
**EMA** Electro-Mechanical Actuator.

**FBW** Fly-by-wire.
**FCC** Flight Control Computer.
**FCS** Flight Control System.

**GUI** Graphical User Interface.

**HF** Human Factors.
**HMDS** Helmet Mounted Display System.
**HOTAS** Hands-On Throttle And Stick.
**HQ** Handling Qualities.
**HUD** Head-Up Display.

**ICAO** International Civil Aviation Organization.

**JSF** Joint Strike Fighter.

**PF** Pilot Flying.
**PIO** Pilot-Induced Oscillations.
**PM** Pilot Monitoring.
**PNF** Pilot Not Flying.

**ROS** Robot Operating System[47].

**SA** Situational Awareness.
**SAR** Search And Rescue.
**STOVL** Short Take-Off and Vertical Landing.

**UAM** Urban Air Mobility.

# Chapter 1

# Introduction

Active inceptor systems are a set of technologies designed for enhancing different activities regarding aircraft control. With this concept, traditional yokes are replaced by electrically powered sidesticks whose main purpose is not only to receive pilot's command and transmit it to the Flight Control Computer (FCC), but also to actively reproduce a force feedback on the inceptor. Additionally, these devices offer opportunities to provide pilots with information regarding flight condition and command state. Furthermore, they enable full integration with other flight assistance devices introduced in recent concepts and newly designed cockpits (see also [11]). Having programmable operating characteristics, they can be adapted and exploited in many environments and for different vehicles. After implementation was initially reserved to military applications, in recent years several installations on civil and general aviation machines were effectively released or planned. Moreover, future evolution of airborne systems could increasingly motivate and facilitate the spread of Active Inceptor Systems (AIS) on a larger number of vehicles. Looking at aviation prospects and forecasts for medium term, three turning points may be currently identified, as reported in [57].

Firstly, aviation, as any other aspect of our everyday life, is requiring to cut emissions and make each of its activities sustainable. A partial conversion to a propulsion based on electrical power or lower environmental impact systems is then expected to happen soon. Moreover, as a second milestone, there is an increasing interest towards very high speed vehicles, for both military and civil applications. Different targets are propelling the research for supersonic and hypersonic aircraft, often with innovative approaches. Lastly, a large number of unconventional crafts are under development and emerging as a whole new class of transportation mean, with a remarkable potential to fill a void in the air transport scenario[57]. Urban Air Mobility (UAM) and electrical vehicles with Vertical Take-Off and Landing (e–VTOL) are doubtlessly making their way on the scene, despite hard technological challenges, mainly for what concerns reliability and regulations.

These changes in propulsion, on-board energy management, overall vehicles' performances and capabilities, flight dynamics and procedures will or already have their impact on the design of the future flight control systems. Nonetheless, all of the previously mentioned turning points could contribute to an increasing interest towards active inceptors. In some cases it is expected that automation will become more and more pervasive in order to manage ordinary operations, leaving to the pilot a higher level of authority, regarding general guidance, navigation and control or exceptions handling. In such a context, human factors and human-machine interfaces hold a paramount relevance in design and operations.

An additional clue on how Flight Control System (FCS) could evolve is offered by forecasts about next generations of military aircraft. The foreseen scenario for the sixth generation of jet fighters, for example, is represented by a single-seat aircraft operating together with a strongly integrated, yet fully autonomous, swarm of unmanned aircraft and drones[40]. Considering such an advanced scheme, and following current evolution of modern cockpit's flight aiding systems (as Head-Up Displays – HUD, Helmet Mounted Display System – HMDS, Hands-On Throttle and Stick – HOTAS, among other) it is noticeable how pilot's information is a prevalent matter. Again, AIS could represent a valid integration to these devices, offering new opportunities to allow pilots to access more effective or differentiated information.

Currently, AIS can be extensively used also in flight simulation assessments, both for training and research, where the possibility to change configuration can be widely exploited. Considering the context of the present essay, an AIS was directly operated, specifically addressing the provision of in-flight haptic cues. This functionality, as later on thoroughly discussed, consists in modifying stick's programmable force-deflection characteristic in order to give to the pilot tactile hints about general flight parameters.

In particular, main focus in the following chapters will be addressed to the question of handling simultaneous and potentially conflicting signals. In general, haptic cueing can prove to be effective on individual targets and with single purposes[55]. Main goal was then to investigate the operation of multiple functions, the possibility to modulate cues' properties and their global interactions with pilots. Specifically, in order to assess this topic, an arbitrating routine was developed. Such module was integrated within a framework comprehending cue-creating programs. The latter were aimed at envelope protecting tasks. Resulting set of experimental modules was then tested and evaluated in a simulating environment including AIS.

Thus, in forthcoming chapters such tasks will be described. Firstly, a characterization of active inceptors and haptic cueing is given. Then, a description of the development process and the technical background behind the arbitrating module is addressed. Afterwards, test and validation phase is reported with relevant remarks. Finally, conclusions and open issues are pointed out.

# Chapter 2

# Active sidesticks and tactile cueing

Following hardware belonging to the command chain for an aircraft control, starting from the pilot seat, the first element encountered is certainly represented by inceptors. As a definition, the latter include all yokes and devices used by the pilots to input their – continuous[1] – commands to the system[3]. Nowadays a wide range of configurations is available for design. The most recent approach is deeply integrated to the fly-by-wire (FBW) technology.

## 2.1 Evolution of flight control and command line

First concept for command actuation in aviation has been a mechanical line consisting of leverages, pulleys and tension cables with the aim to completely link pilot to the control surfaces (see also [41]). It represents the most straightforward approach to the problem of controlling the position of relatively far mechanisms (namely, control surfaces) in the aircraft, and the simplest solution for command transmission. This arrangement features some precious characteristics such as the possibility to have a robust and completely reversible system. It is a closed control loop in which the pilot gives the command and directly receives a relayed feedback through the yokes, related to the resulting force applied on the control surface. A load variation on the control surface would be felt, through inherent transmission advantages and dynamics, on the inceptors.

[1]Commands here addressed are those exhibiting not discrete, discontinuous or state-based operation. Hence, as instance, elevator displacement would have a continuous positional command. On the contrary, landing gear deployment would conventionally have a binary – on-off – behavior. The latter would then be neglected from strict definition of inceptors, as given above. Nevertheless, inceptors could eventually include other types of secondary commands (buttons, triggers, etc).

However, some limits arose as soon as planes increased their size and complexity – so that a need for enhancing control system capability and sizing revealed, as extensively described in [41]. With main challenge being the possibility of exploiting higher control torques, power assisting systems were developed, with the introduction of servo-actuation. In such cases, the design of a fully mechanical line would have required larger and heavier components for transmission and gearing, resulting in global over-sizing design. With the power assisted architecture, pilots command a servo-valve which manages the hydraulic circuit, ultimately applying the control load to an actuator connected to the surface. Hence, from this moment on, control capability was not limited to pilot's strength and mechanical advantages anymore, whereas the hydraulic system basically offered the possibility to include a higher gains in the control law (see also [30]). Despite the significant benefits that followed this principle, some drawbacks were also soon to be accounted for. Mainly, in this case feedback signal is not directly relayed from the moving surface to the cockpit. This principle should be required for pilots to fully understand working condition of the control surface and figure out airplane's dynamical state. Therefore, the concept of artificial feel was developed. Tools – such as springs and bob-weights – were introduced. These devices are able to reproduce a load on the yokes that is proportional to the hinge torque, similarly to that transmitted by a mechanical line. Although complexity was increased, such kind of systems has reached a high level of reliability and have been widely exploited.

Next development consisted in improving the system by making use of electric signals, finally leading to the FBW era[41]. The underlying idea is for the commanding signal to be transmitted to an electro-valve which in turn controls hydraulic or Electro-Hydraulic Actuator's (EHA) load. In this way, transmission is mostly achieved by electric cables, instead of mechanical linking. The hydraulic circuit is limited to the actuation side, allowing to save weight while attaining a comparable level of reliability. The electric conversion of the signals also enabled the possibility to use a FCC to digitally handle the whole control logic. System became more robust, advanced and also reliable[30], enabling less expensive ways to achieve redundancy and to manage a higher number of sensors throughout the control line. Finally, development of electric components paved the way for the concepts of more electric aircraft and all electric aircraft with the idea of realizing homogeneous on-board power generation and distribution across the aircraft. As such, especially for medium-low power level, Electro-Mechanical Actuators (EMA) are becoming generally preferable with respect to the hydraulic ones, reducing interfaces and improving system's control and regulation, removing the necessity for a hydraulic circuit and thus also limiting maintenance complexity[30]. In such a context, it is evident that every component of the command and control line has gone through extensive innovation and advancement during the years. Among them, cockpit's devices, representing the ultimate interface between pilots and vehicle.

### 2.1.1 Artificial feel devices

As aforementioned, once the control system is made irreversible[2], direct feedback for the pilot is lost. Therefore, it has to be restored with appropriate devices which recreate the force feeling on the yokes.

First and most common examples of artificial feel devices are represented by spring or $q$-feel systems[35]. The former is based on the idea of adjusting the stiffness of a spring acting on the control stick relating it to the information of altitude and airspeed attained from on board sensors and instruments. The latter is a system exploiting the same principle: referring to the pressure information coming from a Pitot probe, through a piston or a servo-actuator, load is applied on the control stick, directly connecting it to the difference between the sensed data of static and total pressure. This differential pressure is thus the dynamic pressure $q$, directly related to the airflow velocity, as expressed by Bernoulli's principle[16]. Other devices used for artificial feel purposes are bob-weights, traditionally used for recreating the feel of acceleration, particularly regarding vertical axis and elevator's command response.

All these devices formally aim to fulfill requirements addressing aircraft control and dynamics. Regardless of the type of aircraft, regulations require the command to be intuitive and stable, and to offer a defined level of sensibility and maneuverability all across the flight envelope. Prescriptions like these affect the whole flight control system design whether aircraft's flight dynamics or artificial feel are to be addressed.

As discussed in detail in the next sections, in case of the provision of active sidesticks, most of these aspects are included inside the inceptors' loading system and evaluated by the FCC, making it possible to have extremely complex but flexible configurations and working modes.

### 2.1.2 Human Factors and Situational Awareness

When dealing with control and piloting activities in general, it is absolutely essential to consider human presence as a basic variable of the system. During the 1960s aviation faced a situation in which technology started to rapidly improving, increasing its level of reliability. In such a context, failures due to hardware and technical faults started to decrease relatively. Meanwhile, human errors raised their percentage in causes for accidents[51].

Therefore, in the early 1970s more accurate, systematic and multidisciplinary studies were conducted, aimed to recognize the rationale on human behavior and

[2]With *irreversible* control systems, servo-actuated architectures are here addressed, in opposition to the mechanical, reversible line.

processes which lead to a failure. In this way, formulation and application of several models started, based on the newly conceived concept of Human Factors (HF). HF constitute a complex and multi-disciplinary topic, mostly concerning social, psychological, physiological and technical aspects. This matter investigates on human beings, referred to as fallible entities. Hence, their interactions with all of the counterparts inside the working environment are studied (see also [51]).

This idea can be accurately described through the principle of the SHELL (Software, Hardware, Environment, Liveware, Liveware) model, proposed by E. Edwards in 1972 and then elaborated by F. Hawkins in 1984. It basically states that the human operator (liveware) is variously interrelated respectively with hardware (instruments, devices), software (procedures, knowledge), environment (general surrounding such as noise, light) and liveware itself (including other workers). Singularly analyzing such relations and interfaces, weaknesses and inefficiencies can be found – and corrected – in order to limit future failures.

Since then, aviation gradually accepted these models and outlined relevant suggestions and prescriptions, as with the publication of the *Human Factor Digest no.1* by ICAO in 1989[25], which indeed firstly defined HF, acknowledging its paramount importance for the industry. Later on, this theory led to approach the matter of human error in a completely systematic way, unequivocally identifying possible rationale and causes for a certain incorrect behavior. Ultimately guidelines are proposed to lower risks for errors. In today's acceptation for HF with respect to flight operations, specific branches are referred to flight deck design and flight control design.

Several models have been also proposed for these branches, addressing and classifying human error to fully understand and try to foresee undesired behaviors. Among them, the principle of Situational Awareness (SA) was pointed out. As proposed by M. Endsley in 1995[15], SA can be described as: "*the perception of environmental elements and events with respect to time or space, the comprehension of their meaning, and the projection of their future status*". Hence, to continuously ensure an adequate level of SA to the pilot constitutes a crucial requirement of flight control design. It also becomes fundamental for the aircraft to achieve a sufficient level of Handling Qualities (HQ). In order to achieve such performances, control and command systems are required and expected to comply with several basic principles (for what concerns active sidestick this matter is partly described in [36] and more extensively in [7] and [20]). These principles' targets can be generally summarized as:

- Intuitiveness
- Ergonomics
- Sensibility, Precision and Accuracy
- Acceptable dynamic response[3]

[3] An example of evaluation concerning active sidesticks is documented in [32].

- Univocal command
- Task-proportional load

When these principles are translated into prescriptions, they require the system a proper level of performance. In this way it is possible, for example, to avoid conflicts and offer to the pilot the best setting to continuously reach an adequate level of SA.

## 2.2 Active sidesticks: current state of the art

Active sidesticks are a type of inceptors, specifically, programmable and highly integrated devices, used as yokes for command input of FBW systems, which are capable of directly creating force feedback, artificial feel or tactile cues for the pilot.

### 2.2.1 Main functionalities and potential

Basic concept consists of placing electric motors at the base of the stick together with force and position sensors and provide a bidirectional communication line with the FCC. Such as, it is possible to completely handle the command information through an electrical analog channel (possibly at least coupled with a secondary and digital channel), apply redundancies or find different load paths for control's safety and reliability (as addressed in [24]). Lastly, these devices allow to flexibly change configuration of the whole control system, adapting it to different missions, working states, flight phases or vehicles. With the aim to increase this functional adaptability, these tools have been conceived for longitudinal and lateral control, as side-sticks. Differing from conventional yokes and columns, they offer possibilities to change the control dynamics and improve ergonomics or room management in the cockpit (see also [31]). Furthermore, in this way it becomes possible to adopt new movements and degrees of freedom for the pilot to impart the command. For example in a helicopter, conventional pedal input could be substituted by a lateral sweep of the collective input or a torsional motion of the cyclic (as proposed in [36]). Moreover, the replacement of traditional inceptors with sidesticks is in general favorably regarded also for a more direct implementation of Hands-Off Throttle And Stick (HOTAS) concept. Such principle aims to enhance control sticks' features providing them with additional levers and buttons in order to gather all the main commands on the single device. Thus, need for pilots to release contact with the inceptors is avoided, or at least limited. Both these interchangeability and multi-functionality could represent great advantages in experimental or special operation vehicles, as also in prototypes and new concepts of aircraft.

As already mentioned, there is a growing interest towards new air mobility concepts. These vehicles often exploit unconventional flight profiles and dynamics. In order to have a clearer idea of the context, it could be noteworthy to consider the instance of one of these UAM concept companies (see source at [42]), *Joby*

*Aircraft*. An internal flight control system has been reportedly developed and it is deeply relying (specifically for what concerns the unified flight control law) on the model of the *F35-B*, the fifth generation of fighter, having STOVL (Short Take-Off and Vertical Landing) capabilities and exploiting active sticks[29]. If on the one hand this aspect could not be surprising for the fact that both vehicles exhibit thrust vectoring as the main controlling mean for low velocity flight phases; on the other hand it definitely appears to be uncommon to compare such different vehicles, particularly if referring to a highly specific subsystem as flight control. Nevertheless, focusing on the standard flight profile of these UAM aircraft, it can be seen how peculiar and unconventional they are, especially for the take off and landing phases. From this perspective, it is straightforward to recognize the advantages that a system based on active sidesticks could bring to the control effort, as also thoroughly investigated in [9], since more advanced and complex procedures are involved both for the automatic control logic and for the pilot.

The possibility that air traffic may quite drastically change, poses completely new questions to be addressed when conceiving cockpit design and when pondering pilot's role inside of it. If airways change, also devices that allow pilot to gather information and take decisions could likely follow suit. In such a context, active sidesticks not only open the possibility to access new features, but especially make it possible to provide the pilot with a whole new set of data about flight. Thus, inceptors may evolve and become alerting, informing and guiding devices other than just commanding.

Lastly, there exists another concrete potential for active sidesticks to be used in developing new prototypes thanks to their wider reconfiguration capability. Hence, these devices can be exploited in the experimental research field, especially for flight simulation, where they can already benefit from the most advanced technology to pave the way for secondary improvements. An additional option herein could be the opportunity to simulate a different vehicle's characteristics for in-flight tests. Moreover, it is also noteworthy to enlighten the possibility in the training enhancement[22]. Again, thanks to the wide range of functionalities these device offer, they could be used for example to improve pilots training efficiency by adding specific artificial haptic signals directly to the control sticks. In particular, it would be also easily possible to arbitrarily connect or decouple instructor and trainee commands, enabling new opportunities for training programs.

### 2.2.2 Adoption in aviation

Apart for all potential applications and developments, these devices are in fact already well tested and regularly adopted in several vehicles. They were identified as a safety improving device (as reported in [53] and noticeable in [13] and [14]) and, in fact, proved to increase performance concerning flight control and situational awareness (as described in [23]), besides offering new design opportunities. The technology for active sidesticks has been basically first conceived and developed in the late 1980s (modern principles were foreseen in [18]). Thereafter, it has been tested for military aircraft which were already provided with sidesticks replacing central column, like in some versions of the *F-16 Fighter Falcon*. As of early 2000s, *BAE Systems* began to develop cockpit devices for the then JSF program – later become known as *F-35* – and among them, active sidesticks (as reported in [4] and described in [29]). Simultaneously, much research has been produced and many manufacturers have developed working concepts and prototypes. For what concerns military vehicles, AIS have been also used inside the cockpit of recently updated designs for helicopters as the *Sikorsky CH-53K King Stallion* (as referenced in [10]) and the *Sikorsky UH-60Mu Black Hawk*. As of 2015 such a system had been also pondered for installation in the *Bell 525 Relentless* (utility helicopter) cockpit and, more recently, active sidesticks have found a discrete success for implementation in business aviation vehicles. As instance, *Gulfstream Aerospace* has included this system in its newest designed cockpit for the *G500* and *G600* business jets (reports found in [50], [3]). Lately rumors about a potential first installation onboard of an airliner have come out, generally referring to next *Irkut MS-21* (or *Yak-242*), a narrow-body twin-engine jet that is currently in late test phase and expected to be introduced to market and series production in late 2021.

As of 2020, no plans about implementation of active sidesticks have been documented by the two main airliners manufacturers, *Boeing* and *Airbus*. It is noteworthy to spend some considerations on the reasons why this could possibly not have happened yet, also in order to enlighten limits and drawbacks that however may inevitably be encountered when dealing with a recent technology like this. Firstly, there is a net difference between the approach the two major companies have adopted concerning flight controls. Traditionally, *Boeing* has preferred to always guarantee pilot's complete authority. In latest models, signal from yokes through the FCC, reaches actuators and commands surfaces positions. In case of an emergency related to a failure detected anywhere in the FBW system, pilots are eventually able to switch FBW law to the mechanical backup line. In this way, they are able to directly act with yokes on the servo-actuation, and theoretically also overcome envelope boundaries (as observed in [8]).

On the contrary, *Airbus* has approached this matter in a different way, that is, including pilot's authority inside the FCC. This was achieved by basically granting a higher level of redundancy inside the control laws of the FCC that create the signal to command the control surfaces (as described also in [8]). Depending on the control law, indeed, the commanding signal goes through the ruling logic's process. Such as, the command is more likely oriented on actuation rate rather than on position[8]. Moreover, *Airbus* design already includes sidesticks instead of the conventional control column, although these are used in a passive mode. In case of risky or emergency conditions, practically, the FCC logic is normally set to give priority to envelope protection rather than full pilots' decision, thus preferring to preserve aircraft integrity and trying to avoid additional irrecoverable faults. Nevertheless, sticks are not mechanically linked across the cockpit. Hence, the Pilot Flying (PF) is basically commanding a desired maneuver without the Pilot Not Flying (PNF, also known as Pilot Monitoring – PM) feeling the mirrored input on own inceptors. This point, as instance, has reportedly revealed to be a concomitant factor in the *Airbus A330 AF447* flight accident, at least concurring to degrade pilots' SA. During emergency moments and recovery attempts, this condition eventually led to the fault chain's start (as reported in [50], [6]).

Hence, still the reason why, especially in the latter case of *Airbus*' example, sidesticks are not active and do not exploit tactile cueing features could be questionable. Surely this represents a very specific question which belongs to a wider and highly complex context, where the ultimate reason cannot be unique and straightforward. Anyway, the rationale can be arguably attributed to the increased complexity and cost related to such installations, as discussed in detail in [31]. Primarily, such systems have just started their regulating acceptation and validation path for what concerns civil aviation. Because of the delicate role inceptors perform throughout the flight, it can take a significant amount of resources for companies to first apply for approval procedure. Depending on specific strategies, the implementation of such systems could simply not represent a priority for the company. Furthermore, from the reliability perspective, the introduction of active sidesticks implies quite a bigger change. Indeed, such a kind of installation generally introduces a higher number of new possible faulty modes which can become quite complex to be addressed. As instance, the possibility for the inceptors' motors to report a failure which would end up in the inability to move the stick and loss of control is to be accounted. Such situation could need a wider re-conception of a larger set of subsystems. Finally, drawbacks, especially in the case of an airliner, could become heavier than advantages.

Therefore, main reason could be that, being the current system based on passive sidestick technology, with a proved level of reliability, the entire control logic and software is inherently located inside the complex FCC programs. Processing unit contains all the basis for the evaluation of the specific configuration's signals. Hence, to replace or update the framework to a more complex device would probably require a much more remarkable effort (see also [24]). This principles could explain why the advantages in weight reduction, situational awareness and piloting optimization might not suffice to justify the effort of a design innovation, at least for some classes of vehicles. As aforementioned, though, as the system is becoming more common on board of different aircraft classes, it could be likely that in future also the major manufacturers would at some point decide to share the same approach[4].

[4]Theoretical concerns and concepts are recently even available for general aviation applications,

## 2.3 System characteristics

### 2.3.1 Architecture

Once either the benefits or the drawbacks of an architecture based on active sidesticks have been pointed out, it is possible to focus on the specific system features. An example of the hardware architecture and the device's global constructional layout is pictured in Figure 2.1, with the representation of a commercial model by *Wittenstein*. The actual device is expressly designed for supersonic aircraft (see also [19]), but eventually very similar to the system used for the flight tests that are described in following chapters. In general, from the functional point of view, active sidesticks are constituted by

- The sidestick, ultimate end of inceptor's hardware which is in direct contact to pilot's hand. It is usually designed, as for yokes, in shapes that optimize ergonomics to reduce uncomfortable feeling and fatigue due to high workload. An acceptable operation of on-stick control buttons and levers is also pursued by design.
- A mechanical linkage to control device's kinematics between the stick and the motors;
- Electric motors or permanent-magnets-based (as proposed in [17] and [23]) actuation to develop the required stick force;
- An electronic unit that handles signals and logic together with the controller and software units;
- Force and position sensors;
- Power supply.

The mechanical linkage allows to have the proper advantage through the gearing from the motor to the angle spanned by a stick's stroke. Indeed, generally, sticks' movements are limited within 40 degrees of total deflection. Moreover, it is required to correctly align motor actuation to the relevant command axis, as particularly visible for pedals installations. Gimbals are also commonly used in order to separate different control axes and for position sensors to be installed on. Additional spring systems could be exploited to enable passive or backup modes.

Servo-actuation unit usually consists of two DC motors (commonly working at 28V) for each axis[29]. However, different specific types of actuation have also been proposed. This mechatronic device certainly needs a complex control unit which

as proposed in [34].

Figure 2.1: Active sidestick unit. Image intended for illustrative purposes only. Photography by courtesy of *Wittenstein SE*[19].

contains a CPU for: mode switching, motors' regulation or monitoring, general signal processing and also interfaces with central FCC, servo-actuators and force and position sensors. The latter usually are present in triple configuration for reliability's sake (as described in [29]).

A diagram for a typical architecture of FCS, that includes active sidesticks (as also reported in [23]), is pictured in Figure 2.2, where the continuous arrow represents a direct action or signal, while the dashed line denotes an information conveyed from a sensor or, in general, a sensible feedback. Thus, it is noticeable as the pilot may usually give inputs directly on inceptors or managing FCC settings from the cockpit. The information of commanded sidestick goes to the inherent control system containing the specific electronic unit. The latter can directly act on the inceptor or in general communicate with the FCC. If a command is required, related signal goes out to the actuation unit which eventually activates the control surface's motion. Finally, aircraft undergoes the effects of such intervention and its dynamics consequently evolves. All the blocks have a specific network of sensors whose information is sent to the pilot and the FCC. The main difference from such a system with respect to one based on passive inceptors is found in the red feedback arrow in Figure 2.2. If yokes are passive, such feedback is realized through artificial feel devices (for FBW aircraft). In case the inceptors are made active, the feedback they bring is enhanced, offering the pilot a new channel for gathering information, other than typical cockpits' instruments and external environmental clues. From this overview, such system appears a logical implementation aiming to improve the command line and achieve a complete control network around the pilot.

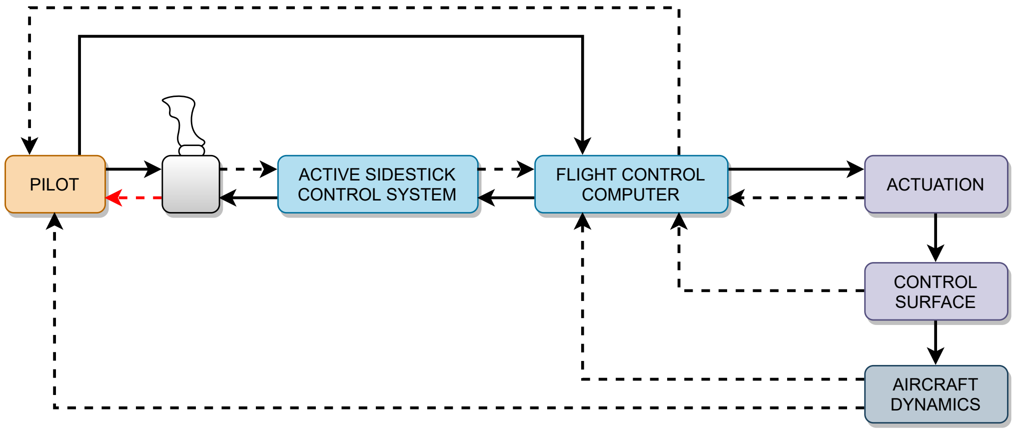


Figure 2.2: Diagram of the architecture for a flight control system provided with active sidesticks

### 2.3.2 Tactile cueing specifications

Thanks to the improvements in computational power and mechatronic technology, nowadays it is possible to alter sidesticks dynamics with complex laws of control, yet without affecting actuation speed, precision and reliability. Hence, it is possible to intervene on the feedback branch of the control loop in order to give the pilot much more information about flight and machine state. Main advantage is that in this way pilot's reception is accessed upon a tactile layer which can prove to be a more intuitive, direct and generally fast way of stimulating operator's reactions and awareness (as reported in [23] and described in [2]). Nevertheless, pilots' sight and hearing is not affected, thus providing alternative channels for information. Tactile cueing decreases stress caused by working overload, lack of focus, mistaken troubleshoots or general shortcomings, especially in delicate or critical maneuvering situations[23]. This matter, hence, strictly relates to human factors and human machine interface other than flight control itself, yet providing a further degree of freedom in design process.

### 2.3.3 Haptic cue and force-displacement curve

Active inceptors' functional concept is based on a working curve that refers each position of the stick along a direction to the correspondent force the pilot is supposed to feel. This force is computed in relation with the current flight condition as well as to a set of other different parameters. This function is managed by the processing unit of the control loading system eventually after reception of external inputs coming from the FCC. Sidesticks' state and FCC computations are ultimately used, together with sensors' data, to build the electrical signal that feeds the stick's actuation drive. So doing, appropriate force feedback is created.

The simplest basic function of the force with respect to the position represents a linear and proportional relation. It aims to reproduce the elastic force function of a spring-based artificial feel. As previously mentioned, the latter stands, in turn, as a linearization of the function relating the hinge moment (and, more properly, its transmission at the yokes) to the control surface deflection. The basic function of stick force with respect to deflection is usually referred to as master curve. It is generally defined as a linear function with the slope that represents the stiffness of the command with respect to sidestick displacement. Master curve's gradient can be generally set and changed at any moment. Different slopes for forward and aft displacements of the stick may be also given, in order to represent an asymmetrical stiffness of the inceptor. This finally reproduces a possible asymmetry in the actuation, aerodynamic design or performance of the control surface. Although this behavior is rather uncommon for conventional vehicles, this feature could have experimental relevance. This gradient may also be varied by an external parameter that replicates the $q$-feel effect of an artificial feel system. In this way, controls are stiffened with speed. When velocity is increased, dynamic pressure also grows. If this property is active, gradient of stick force curve will be proportionally increased. This principle is also referenced in regulations and guidelines for good HQ. The main advantage in the use of active sidesticks is the possibility of externally change force-displacement curve's definition (or also stick's dynamic model, as proposed in [33]). It can be shaped in relation to a wide set of events and configurations and, eventually, even during flight. Particularly, it is common practice to overlap, to the underlying master curve, some predefined curve patterns that represent different cueing behaviors. These shapes can be adapted to the specific function through a limited number of properties (cue type, start and end coordinates or dimensions) that make insertion or alteration extremely easy to apply. Hence it is possible to define some preset, standard functions that model the most common cueing shapes, such as:

- Hard-stop: segment of the characteristic function at constant displacement of the stick (fixed). The effect for the controlling effort is a complete lock in place in the command-wise direction for a limited range of commanding effort. The station is then eventually overcome if the force is applied beyond a defined value. However, this type of cue is usually only used at the ultimate ending positions along the axis. They also would have weak control of the hard-stop's maximum load, thus experiencing a further deflection when overcoming effort. Pilot would find the force step as a rough interruption or slip, depending on the direction of deflection. In this situation, inceptor would very likely end up in an unwanted and unfavorable overshoot, as examined in [46].

- Soft-stop: this type of cue is the most common one when dealing with tactile cues because it proves to be rather intuitive, yet not too intrusive, to be implemented into the control and command activity. It consists of a change in the slope of the curve, usually increasing load's derivative in the positive command direction. Pilot would then feel this cue as a hardening of the control device, the further this one is taken. This haptic shape turns out to be particularly effective when adopted to warn the pilot that a maneuvering limit is getting approached. Also, subsequent gradient changes all along the displacement range prove useful to inform pilots about different parameters. Usually, in correspondence with the null displacement position, a breakout segment is often also arranged, to define and denote reference deflection position. It stands to replicate the effect of friction on released commands. In general, stick's breakout force and friction are also requirements prescribed by regulation and, together with trimming performances, are aspects that concern aircraft's HQ. This definition also affects trim setting, as described in [7]. From the perspective of function's definition and operations though, breakouts can be considered analogous to aforementioned soft-stops.

- Detent and gate: these cue shapes are usually adopted to signal the pilots with the overcome of a defined station. Detents are realized with a slip in counteracting force, soon followed by a relevant recover. Gates are defined in the opposite way, that is achieving a slight increase of stick force followed by an even decrease. The effect is as a light, strictly local, stagnation of the stick. When used in combination, they also favorably get pilot's command in a rather defined position, yet in a softer and stabler way than what is achieved through a hard-stop. Moreover, the concept of holding the command applies for either positive or negative force applications, differently from the hard-stop. Effect felt by the pilot is a more or less stationary position, with defined threshold values of required force for further movements. Once the threshold force is overcome, usually the resistance of the yoke is shortly decreased and, thereafter, it normally follows the underlying curve. The advantage in the adoption of this shape is that it usually occurs when a certain intermediate position could reveal considerable for the pilot to simply hold with a slight effort. Hence this tactile cue is ideal for controls that involve temporary discrete inputs, as, for instance, throttle.

The analytic arrangement of the force-displacement curve is reported, together with some examples of the mentioned cue shapes, in Figure 2.3.

Apart for these shapes, control loading systems for active sidesticks generally

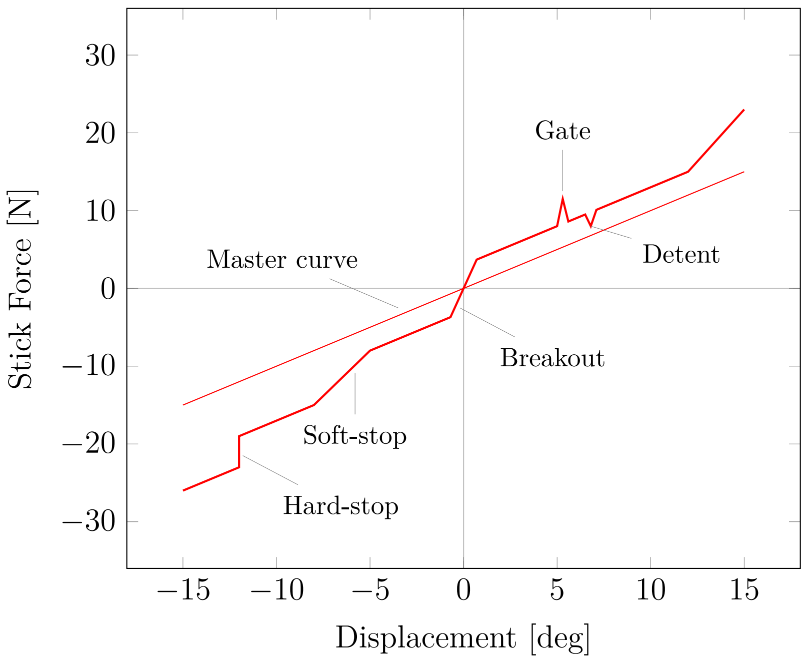


Figure 2.3: Example of a force-displacement curve for active sidesticks

also offer several different options. It's noteworthy to outline that paramount importance relies on the friction definition. The latter, besides the previous considerations, has to be cautiously managed by the stick's processing unit because it could indeed become a dangerous and delicate factor inside the control loop performance, leading to oscillations and alternating motions which obviously should be avoided. For this reason, it is usually possible to calibrate system's properties – such as sensors tolerance and static and dynamic friction coefficients. For sake of simplicity, in general, a Coulomb friction model is basically referenced.

Another important parameter that is possible to arbitrarily set is the $q$-feel module, as above described. Moreover, being a complex dynamic system, active sidesticks also offer the possibility to change the basic dynamic model for different frequency-defined responses. Furthermore, modern control loading systems and AIS provide punctual control features like the definition of end stops, zero and reference position (useful to enable trim functions), axis linking and coupling (as in [49]).

Lastly, different tactile cues based on stick-shakes are also available in most of the systems. Although in principle this approach could have an exceptionally wide range of potential application, some drawbacks can be raised in the operational environment (as resulted from [39]). As outlined for other shapes, once complex active functionalities have been brought to a sidestick, the most important aspect often lies in the necessity to prevent that any possible cueing signal coming from the control logic would ever cover, mislead or takeover pilot's will, authority and awareness. In this context it appears to be self-contradictory to induce a sidestick shake for the pilot to move the yoke, especially in case of parallel directions of the motion. This conflict could be experienced regardless of the characteristics (frequency, amplitude) of the cueing shake and general flight situation. Haptic cueing functionality is indeed completely effective when it exclusively acts on the force of the command, while leaving to the pilot a clear feeling and tactile identification of inceptor's displacement. Moreover, such a shaking feature conceals the risk of becoming basically degraded in a moderately-high vibrating environment – as helicopter's cockpit is. Furthermore, during stressful or high workload requiring missions, it could contribute to pilot's mental (especially if the cue is poorly intuitive) and physical effort. A remarkable point of analysis is also the risk of concurring to the start of Pilot-Induced Oscillations (PIO) in case the shaking cueing function has a relatively low frequency (as signaled by [55] and generally described in [28]). In the latter scenario, which is an important case of poor HQ performance, pilot would react to stabilize aircraft dynamics by amplifying an oscillating mode because of the phase lag between pilot's command reaction and aircraft's mode itself. Notwithstanding the latter drawbacks, it is still noteworthy to point out that general haptic cues based on shakes could however have significant advantages. As instance, this characteristic efficiently draws commander's attention and is widely exploited in the video-gaming industry. Nevertheless, in this case a substantial remark is that shake acts on a completely different tactile level than control[5]. Thus, the necessity to separate and uncouple either the shake device or its movement from the controlling engagement should result straightforward. This step, though, would be the hardest challenge to implement for a cockpit where clearly inceptors are commanded with hands and feet (so basically no ergonomic control axis is free for this type of cue). Moreover, adding further external and on-purpose devices would generally be not convenient. These observations could outline difficulties in operation of the shaking cueing functions. The latter, however, also have much potential that is worth to be further investigated.

[5]Classical gaming nowadays is considerably not completely distinct from the flight simulation world – hence in some elementary ways it is even relatable to piloting duties. Concerning gaming, usually, levers and buttons are activated only by user's fingers. If a shake function is present, it evidently acts making the whole controller vibrate, thus operating on whole hands and arms' reception and basically without interfering with fingers position.

### 2.3.4 Envelope protection

As previously mentioned, tactile cues are haptic feedback signals for the pilot to receive. These can be provided for sake of information, assistance, and warnings about current flight status. One of the purposes for which tactile cueing has actually proved effective is to notify pilots about flight envelope boundaries (as discussed in [58]). Flight envelopes are diagrams which plot aircraft's allowed performances for safe and controlled operation. Main and most common envelopes are referred to as Operational Flight Envelope, Service Flight Envelope, Permissible Flight Envelope and concern performances in terms of combinations of variables such as: flight altitude, horizontal or vertical speed, but also turn speed or load factor. In general, diagrams typically point out peculiar effects and boundaries on performances such as the velocity to never exceed. Due to helicopter's inherently different flight mechanics with respect to conventional airplane, also flight envelopes slightly differ, as explained in detail in [54]. Other specific behaviors for the helicopter to always keep under control are torque request and sink rate. All these conditions prescribe limits and regions with different level of practicability.

Nevertheless, it is important to mention how envelopes define aircraft's areas of designed, tested and allowed operations. In every point of the envelope, each component, as well as the global vehicle, is at a certain fraction of their maximum performance. The latter could have been defined for safety, functional or maintenance-related concerns. However, it is important to outline that, once the envelope is globally defined, it would be inefficient to prevent operators to approach its boundaries and regularly use its entire area. For some of the limits, also, operations are not strictly defined as completely forbidden areas, because of their inherent nature. As instance, the case of the engine could be considered.

In twin-engine helicopters power units are usually operated at a fraction of their maximum performance, for sake of reliability and maintenance, due to the high stress of components like the gearbox. Nevertheless, temporary overloads are often allowed in case of emergency or demanding maneuvers. Moreover, and this factor could be less intuitive, during flight it could happen that a pilot, underestimates machine's capabilities or misjudges the situation. This situation could occur because of lack of awareness on vehicle's state or for a malfunction. It would lead to maneuver complications, unexpected stress on different parts or a fail for mission accomplishment. In many situations, hence, it could not continuously be possible for the pilot to exactly realize and evaluate the margin of allowed maneuverability.

For these reasons it proves reasonable to provide the pilot with a system that anticipates or warns in case of limits approach. In such a way it is easier for the operator to get close to envelope's boundaries without overcoming them, therefore exploiting the most of aircraft's performance without reducing safety and reliability or increasing risk. A clear instance for this application is found, for what concerns helicopter, in the limitation of the requested and required torque following a collective lever lift, as extensively described in [38] and [37].

### 2.3.5 Rotorcraft application

The technology at the base of tactile cueing has found a particularly valuable field of application for rotorcraft. Differing from fixed wing and conventional planes, these machines have a peculiar – and typically more complex – dynamics of flight. In simple terms, they would add an extra command variable consisting of the collective lever for vertical flight.

Technically, thanks to this specification, the helicopter can be commanded to move independently along the three axis, even starting from a hover condition. Nonetheless, there is a high level of interconnection among different axes actions, for the inherent flight mechanics' model. Each one of the commands has non-negligible side effects on most of the other planes' motion. This property alone could sufficiently outline the potential of a complex and performing FCS. Furthermore, due to this inner complexity, even found in the conventional architecture of the helicopter, flight performance's grade has paramount importance from a reliability and maintainability viewpoint. Helicopters typically exhibit high number of components and technology's cutting-edge level required for some of the most critical ones. This aspect makes it strategical to search for devices which, with the least possible expense (in terms of complexity and cost), are effectively contributing to protect different parts of the vehicle.

Because of inherent design, limit maneuvers could have a heavier backlash on the machine life-cycle if compared to fixed wing aircraft. For this reason, haptic assistance through inceptors is particularly effective in helicopters for assessments aimed to warn the pilot about the current flight condition with respect to envelopes' boundaries (an application for load factor is described in [56]). Envelope protection tasks are indeed one of the most focused research applications, as in [48], [58] and [1]. This point in the case of helicopters is outlined in [21].

As previously mentioned, to this date, this technology has mostly military applications (*Sikorsky CH-53K King Stallion*, *Sikorsky UH-60Mu Black Hawk*[55], *Boeing MH-47G Chinook*). It is interesting in this case to point out a solution proposed by *BAE Systems*, namely the LinkEdge system[5], which allows to introduce active sidesticks in machines without a FBW system, linking the inceptors to the command line through a clutch transmission. In such a way enhanced handling qualities and control features can be attained for machines that require service updates and improved performances. Active sidesticks have been reportedly installed in the *Bell 525 Relentless*, although this model is currently still undergoing the certification process through final validating tests. Nonetheless, several examples can be found in publications for what concerns successful experimental installations and many trustworthy developments have been performed in simulating environments.

### 2.3.6 Flight simulation

On-board application of active sidesticks can be seen having a gradual integration across different vehicle classes. For what concerns flight simulation, this integration can be surely straightforward.

Flight simulators, indeed, require such kind of devices ab initio. In order to reproduce aircraft's state and condition with good fidelity, it is essential to provide the pilot with realistic feelings and perceptions. Once more, active sidesticks, allow to recreate this feedback, for example the one related to $q$-feel, more accurately than with passive spring systems. More importantly, it is possible to widely change inceptor's characteristics to adapt it to simulate different vehicles, enabling the possibility to change configuration.

Furthermore, it could be noteworthy to summarize the simulation environment in which these devices operate. For what concerns the helicopter, which has constituted the model used in the activity for this essay, the approach for flight simulation is analogous to that of fixed wing models[52], except for the dynamical equations that differ from that analysis. With this premise, general system of equations of motion can be written. These include[16]:

- Force equations in body fixed reference frame, generally expressed as:

$$\begin{cases} F_x = m(\dot{u} + qw - rv) + mg\sin\theta \\ F_y = m(\dot{v} + ru - pw) + mg\sin\phi\cos\theta \\ F_z = m(\dot{w} + pv - qu) + mg\cos\phi\cos\theta \end{cases}$$

- Moment equations in body fixed reference frame, in the form:

$$\begin{cases} L = I_{xx}\dot{p} - I_{xy}(\dot{q} - pr) - I_{xz}(\dot{r} + pq) + (I_{zz} - I_{yy})qr - I_{yz}(q^2 - r^2) \\ M = I_{yy}\dot{q} - I_{xy}(\dot{p} - qr) - I_{yz}(\dot{r} + pq) + (I_{xx} - I_{zz})pr - I_{xz}(r^2 - p^2) \\ N = I_{zz}\dot{r} - I_{xz}(\dot{q} - qr) - I_{yz}(\dot{q} + pq) + (I_{yy} - I_{xx})pq - I_{xy}(p^2 - q^2) \end{cases}$$

- Kinematic equations that relate angular rates with Euler angles
- Navigation equations to obtain the velocity vector in Earth bound reference frame.

Hence, force and moment terms acting on the aircraft in the first two systems are decomposed in the aerodynamic contributes along the relevant axes. According to the adopted level of approximation, these equations may alternatively neglect or account for different secondary terms. For the helicopter, however, expressions for forces and moments are generally obtained separating the effects among main contributions to overall performance. These effects, for first model approximation order, as proposed in [44] and [27], are:

- Fuselage (and empennage) aerodynamics with body degrees of freedom. This expression yields forces and moments as functions of the variables of state (including components of velocity, angular rate and Euler angles)[52]:

$$\{x_F\} = \{u, v, w, p, q, r, \phi, \theta, \psi\}^T$$

- Rotor aerodynamics, with the blade state analysis function of blade's degrees of freedom (namely flapping $\beta$ and lead-lag $\zeta$ motions) in the rotating frame that are in the form (if first order dynamics is referenced):

$$\{x_R\} = \{\beta_0, \beta_{1c}, \beta_{1s}, \zeta_0, \zeta_{1c}, \zeta_{1s}\}^T$$

  Analogous approaches are used for tail rotor dynamics.

- Inflow and downwash effect can be calculated separately and can be written in terms of the dynamic inflow coefficients:

$$\{x_I\} = \{\lambda_0, \lambda_s, \lambda_c\}^T$$

- Powerplant and drive train dynamics, depending in general on rotorspeed $\Omega$ and engine torque $Q_e$.

$$\{x_P\} = \{\Omega, Q_e\}^T$$

- Additional equations related to specific flight stability and control augmentation systems

Equations in the resulting system can be written in the explicit form

$$\dot{x} = F(\{x\}, \{u\}, t)$$

Where $\{u\}$ command variables' vector, containing the terms for collective, cyclic (lateral and longitudinal) and tail rotor's blades' pitch[44]:

$$\{u\} = \{\theta_0, \theta_{1c}, \theta_{1s}, \theta_{tr}\}^T$$

These variables do not correspond to the actual inceptors' (respectively, collective lever, column for longitudinal and lateral cyclic and pedals) displacements. If the latter are referenced, additional relations should be accounted, adding control variables and equations to the system. In case active inceptors are used, for a higher level of approximation, the expression for their dynamical model could even be included in the system, since it influences command state variables (as described in [33]). Thus, presence of AIS, as well as passive yokes, generally have an effect on the dynamical systems' analysis. It is then straightforward how the possibility to rather instantaneously change inceptors' inherent response could be used to affect or modify aircraft's flight mechanics. In fact, before being used as artificial feel devices in aircraft, AIS were firstly conceived and introduced for flight simulators[2]. In this context actuation of inceptors became soon a requirement for good fidelity of complex systems. For this application, they were initially realized with hydraulic actuators and, after progresses in mechatronic devices, electric motors were finally used, as described in [2].

The complete system's equations are in general nonlinear. They can be used to calculate trim conditions, starting from a set of initial parameters and computing the convergence for time constant state variables. Finally, equations of motion are integrated for time variations[44], typically using forward numerical methods. Starting with initial conditions, forces and moments are iteratively computed updating state variables with time increments. As described in following chapters, the environment used for developing and testing new proposed functionality was based on the flight simulation of a nonlinear helicopter's model in which an AIS was used.

# Chapter 3

# Tactile cues arbitration and prioritization

Once general technological background and context have been described, it is possible to focus on the actual operational environment in which tactile cueing is typically involved and describe the attained approach for experimental study. Moreover, it is possible to present and focus on the specific software arrangement and on the assessments that were performed on the system.

## 3.1 Haptic cues operation

Working principle for haptic feedback on active sidesticks is straightforward, especially in case of envelope protection. Yet to optimize the process and make it completely reliable could become demanding. During flight, force and position data from the sidestick unit and general flight data from the FCC are sent to the processing module for the cue calculation. Here, the specific limit is evaluated, either directly with the available data or through more complex model based computation. After this stage, one or more limits are defined. Then, they are processed in order to build required cueing force-displacement functions. Once the cue insertions or the modification for the force-displacement curve is computed, the data are sent to the control system for the sidesticks through their proper inherent protocol, which then realizes the actual change of the working parameters.

A noteworthy matter here is that, during flight, not only the position of the stick could continuously change following pilot's command, but also the stick force curve itself, according to flight's dynamic state changes that induce a modification to envelope parameters and limits. It is important that the change in stick force definition be completely transparent to pilot. Commands should update their working function without causing confusing inputs for the pilot to be felt.

As instance, considering the pilot in a condition for which the inceptor lies on a pre-defined softstop and supposing the aircraft changes its dynamical state after a certain amount of time. In the new condition, the softstop could have changed its definition or also moved to a further station. Thus, stick force needs to reset on a – perhaps not negligibly – different level. The system has to reconfigure its parameters in a mostly imperceptible way, that is, the pilot should feel the force gap but avoiding instantaneous or abrupt changes which could lead to poor comprehension of the haptic feeling. To solve this problem, different workarounds are usually applied. Among them, it is useful for the system to have high frequency update rate or also a defined rate of change for curve update which allows the pilot to perceive the force variation as a change of conditions and not as a new cue or signal apart.

## 3.2 Arbitration module

Starting from a framework consisting of all technologies that support active inceptors and tactile cueing systems, final target for the task herein described has been to address and analyze a rather specific condition for these devices to be operated in. As described in previous sections, active sidesticks' technology offers several features and has remarkable potential. For this reason, many are also the possibilities to focus on a particular behavior, to deeply study a new application or to analyze performances in a detailed situation. Within this wide range of experimental research chances, the chosen goal has been to further investigate on the presence and interaction of multiple haptic cues on the same system of active sidesticks, specifically referring to helicopters. This matter has then become the central topic for the study assessment and is next described.

### 3.2.1 Arbitrating task

Once an AIS is provided and different haptic functions – as for example, cues triggered by envelope protecting modules – are all singularly arranged and optimized for regular application, main issue becomes to handle them in set. Thus, the question arises: how are they going to operate altogether?

Particularly, considering a flight situation in which multiple cues are active, two points of view to discuss about are raised. One is basically technical: how are they working with respect to each other from a systemic perspective? Are they merely overlapping or do they need to be expressly processed, for the system to be working efficiently? In the latter positive case, following evaluations would inherently define a first milestone to the global development. However, considering current state of the art, a good management of overlapping cues is already provided by the sidesticks' controller that usually neglects or forbids the definition of a cue that would overlap an existing tactile function.

Second and main question is wider and, eventually, includes first point's considerations. It closely deals with pilot's flight perspective and, specifically, with operator's perception. In this case the topic consists of how pilot perceives information from differently aimed cues. More specifically, question would be: is it effective to let parallel and simultaneous haptic signals to act without modulate them? Furthermore, case of complex cue patterns, conflicting function acting concurrently or possibly overlapping interventions is conceivable. Issue to be addressed would then be how can the system be managed in order for the pilot to focus on most important information and, more specifically, avoid confusion.

Hence, it becomes clear that to introduce the possibility to manage cueing intervention in a systematic way and with a good level of authority could be strategic. This concept could also reveal benefit coming from eventually different approaches to this kind of flight assistance. The possibility to control each cues' level of intrusiveness in the command activity could then be favorable. Nevertheless, results highly depend on how such feature is implemented in the system.

Ideal solution would be to have a highly integrated and complex unit which is able to, not only regulate cue's parameters statically, depending on flight condition, but also depending on all inceptors state and on pilot's level of perception (a possible initial approach is described in [26]). Again, perfect system would send cues to the pilot on point. It would discard all possibly confusing feedback and provide target- or mission-related haptic clues, besides that safety ones.

As instance, it could be useful to imagine an helicopter operating in a near-hovering condition. A tactile cue could be notifying the pilot when approaching the vortex ring state in case of the acquisition of a slight descending speed. A complex cueing module could in this case intervene by, for example, modulating the other possible active cues. Clues would be sent for the pilot to undertake the best maneuver to exit the condition, evaluating different parameters such as aircraft state, flight variables, environmental setting, mission requirements, etc.

If such kind of functionality is perhaps projected further than the current potential and utility of the system, it helps to clarify which could be the latest goal set for technology to reach. Meanwhile, this approach is also useful to enlighten what could be a good strategy to implement smaller developments. As described in the following sections, in the case of this assessment, this consideration has been helpful to lead to a more general approach. As instance, this was one of the reasons why it was preferred to address cues on the base of their possible scope or assigning them relative (and often re-configurable) values, rather than strictly preconceive their setting.

### 3.2.2 Module and interface development

After all the considerations concerning the general problem of managing possible interaction among different cues, the specific environment was addressed. Existing framework used for this work is globally described in [12], although it was occasionally adjusted and slightly updated for purposes of integration with new module.

However, the software environment basically consisted of:

- A main interface, constituting the junction between the inner simulator frameworks and the experimental unit. This includes recently developed routines for haptic functions handling and AIS inherent software. It allows system monitoring and setting, managing the entire simulator's configuration.
- A torque protection module, calculating needed data for the tactile cue that limits required torque.
- An application, entirely developed and described in [45] for velocity to never exceed. It makes calculations for a haptic cueing function to limit and warn on maximum speed.
- A module for bank limitation, created to provide a cue which signals the limit on reached roll angle during maneuvers.

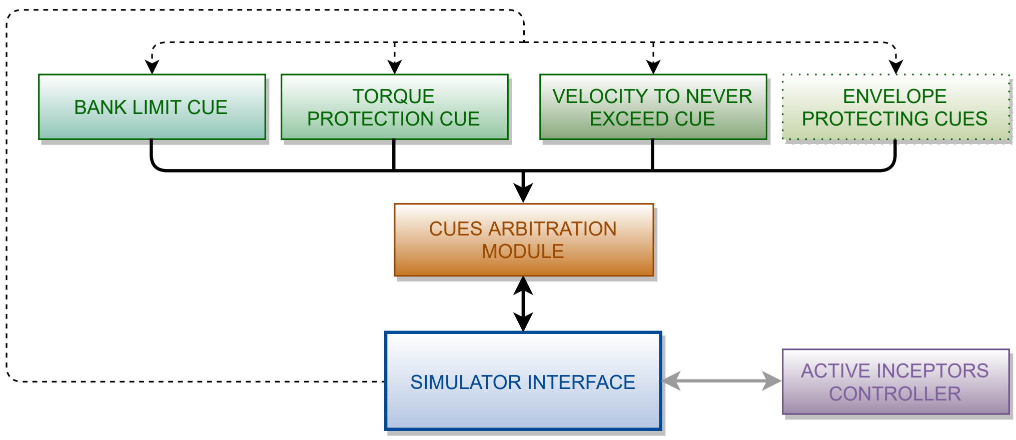


Figure 3.1: Diagram of the communication pattern for the arbitration node

As depicted in Figure 3.1, the cue calculating modules send data to the arbitrating block, purposely written to handle different, simultaneous or conflicting cues. Other external envelope protecting modules can also be added, similarly to how the present ones are connected. The insertion of additional cue functions has been symbolically referenced in the diagram, but also predisposed within the arbitration module configuration, for potential future adjuncts. After the evaluation required by the arbitrating and prioritizing task, selected cue-implementing instructions for the inceptors are sent to the simulator's interface. Afterwards, they are forwarded to the sidesticks' controller. All communications among these modules are set using

*ROS* (Robot Operating System[1]) frameworks, based on nodes that are publishing and subscribing to messages. The latter are targeted under defined topics.

The two-ways channel (reproduced in gray in Figure 3.1) between the simulator's module and the inceptors' unit consists instead of a specific inherent protocol.

Finally, the cueing modules also communicate with the main simulator interface. Specifically, they receive the flight data they require to evaluate envelope boundaries. Such channel, although still based on the interface block, is functionally slightly different from the others, as it basically refers to the helicopter's state vector. Hence, such line of communication could be actually considered independent from the other types. However, framework is eventually shared and integrated, as results from the dashed line in Figure 3.1.

The arbitrating routine, that will be described in the next section, has been written in *Python* and provided with a Graphical User Interface (GUI) to set different options. GUI was developed with *Qt* and *PyQt5* frameworks.

### 3.2.3 Specifications

The module intended for arbitration has been conceived with some technical implicit requirements. Such as, it was intended to be fully integrated with the preexisting framework and compliant with all the parts of the system, requiring for them the least possible change. Moreover, it had to share the same channels and protocols for communication. Also, it should have been arranged and built with a high level of flexibility for features to be extended or added and to, eventually, grant multiple possibilities of configuration.

From the specific functional point of view, instead, the routine was conceived aiming to reproduce the diagram in Figure 3.2. For all main features, details will be provided in the following sections.

#### Interfaces description

As aforementioned, the program consists of a main GUI that allows users to set general properties for the configuration. The interface, as illustrated in Figure 3.3, shows different tabs referring to external cues built for envelope protection purposes. Each tab has the possibility to control four different cues. User can select a cue and edit its main properties. It is then possible to arbitrarily add cues or trace cueing functions generated by the signal coming from external protection modules. If one or more cues are automatically created and bound to an external module's signal, they appear as selected by default. Currently, it is possible to customize

[1] *ROS* is an open-source collection of libraries, protocols and conventions that aim to simplify the task of creating complex and robust robot behavior, integration and communication across a wide variety of robotic platforms[47].

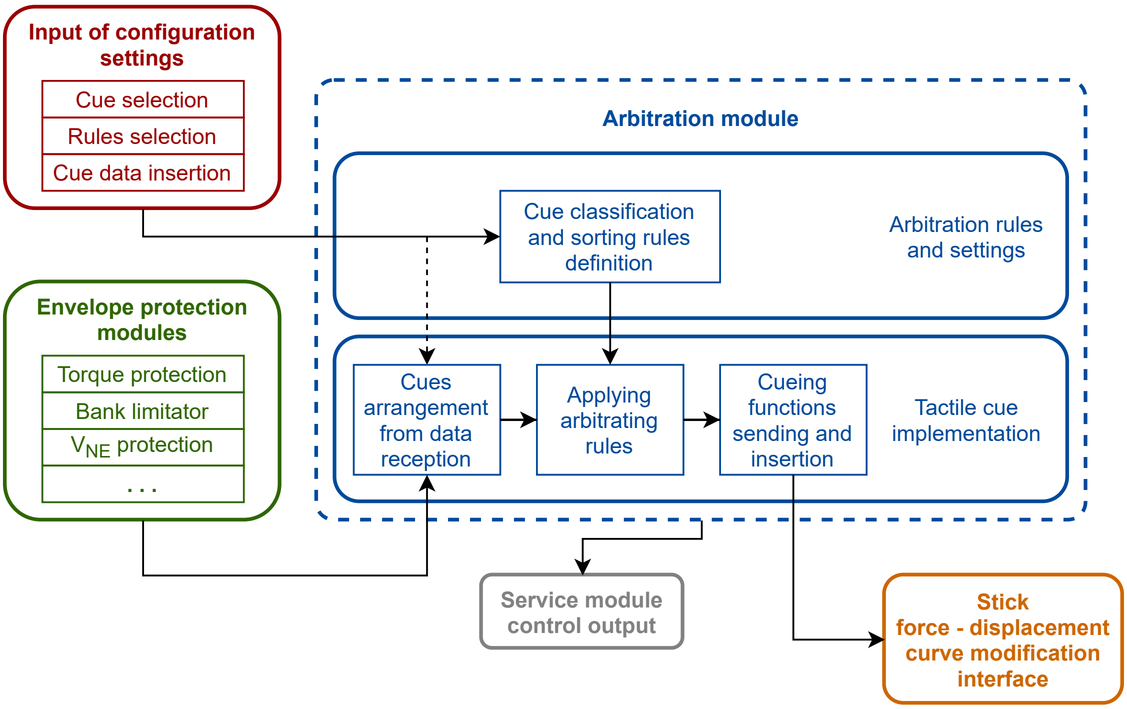


Figure 3.2: Functional architecture of the arbitration module

cue's properties, directly from the GUI. Received signal, at the moment, always and only consists of the start position of the cue on the force-displacement curve. Since only simple cue shapes have been considered by now, this arrangement results to be sufficient. On main interface also three action buttons are provided:

- *Reset*: allows to send signals that reset properties for every possible cue implementation which is not currently active. It had mainly debugging and test purposes, as it was used in order to change configuration without having to reboot other simulator's components or programs.

- *OK*: sends the instructions for all cue's definitions added by the user directly through the interface, after edit is complete. At application's start up, also allows to initiate and enable publication of cues that are bound to external modules, after the user has eventually modified their properties. In case a custom cue has been switched off it also sends the relevant signal to the inceptors console, in order to delete cue's properties.

- *Options...*: opens the GUI for the options dialog window.

Secondary interface lets the user select different properties to control routine's configuration and select different settings, such as:

- Cue cross-coupling: it is possible to enable cross-coupling for pilots' haptic feedback through the cockpit. General cross-coupling feature allows the reproduction of a mechanical link between inceptors' axes, in such a way that the displacement is common on each corresponding command at both seats, as described in [49]. Within present program's perspective, this property applies to cues. This means that, if cue cross-coupling is enabled, cues set on one axis will promptly be reproduced also for the other pilot. As a consequence, relevant force-displacement curves will be equal, and there will be no discrepancy for one stick's effort and displacement.

  This feature is peculiar because if basic cross-coupling is active, master curves for the two pilots are the same. Now, if one cue is added only for one pilot – suppose pilot's command to lie within the cue's boundaries – applied effort will be different with respect to the master curve. What would happen on other pilot's stick is that it will follow its underlying definition. Thus, pilots would have same sticks' deflection with different force. In case softstops amplitude is not negligible, pilots would feel confusing behaviors. This situation would result in one pilot's command to be affected by both its own inceptor's curve definition and by other pilot's command which, in turn, relies on a different force-displacement definition. Situation just described could be acceptable for an inherently uncoupled system where an appropriate and dedicated control logic would process the force-position data with respect to a defined control law. On the contrary, command perception would be altered and degraded for cross-coupled commands.

  If the system is set to be cross coupled, also the sent cues have to follow the same principle. Rationale for this option to be present is then easily deduced.

- Arbitrating rule set: among presented options, remarkable relevance is attained by the selection of rule set. Basically, three laws for cues' prioritization and filter are provided:

  - Idle: enables all the cues that have been set. Sets the arbitration in a passive mode to test or use the program without any specific impact.
  - Cue shape: prioritizes and sorts list of enabled cues by their cue shape. If this rule is set, it is possible to choose one or two cue shapes to be filtered (as listed below).
  - Priority: sets priority property as ruling criteria and lets user decide which levels to allow and which ones are to be filtered out and discarded.

- Protecting modules: this section lets user address main interface's tabs, enabling or disabling their underlying cues. If an external module for envelope protection is detected to be sending required data, corresponding tab is automatically enabled and one or more cues are reserved to such function. From the interface it is possible to disable external module's connection, thus clearing reserved cues or also change the number of active cues which rely on the module communication. Such functionality, already exploited for the bank limiting routine, may be especially used in further developments and program expansions, in case several shapes are to be connected to one envelope-protecting function.

Options window is also automatically showed at module start up. This occurs in order to let the user check initializing settings and layout. For this reason, options' control window is also provided with an *Update* button. The latter is only enabled right at start up and allows to reboot the connection attempt with external modules in case topics were not detected properly. In such cases, this feature prevents the need to abruptly close and restart the application. Once modules are connected with the right number of signals, it is possible to go to the main interface, change cueing shapes' properties and send implementing instructions as summarized below.

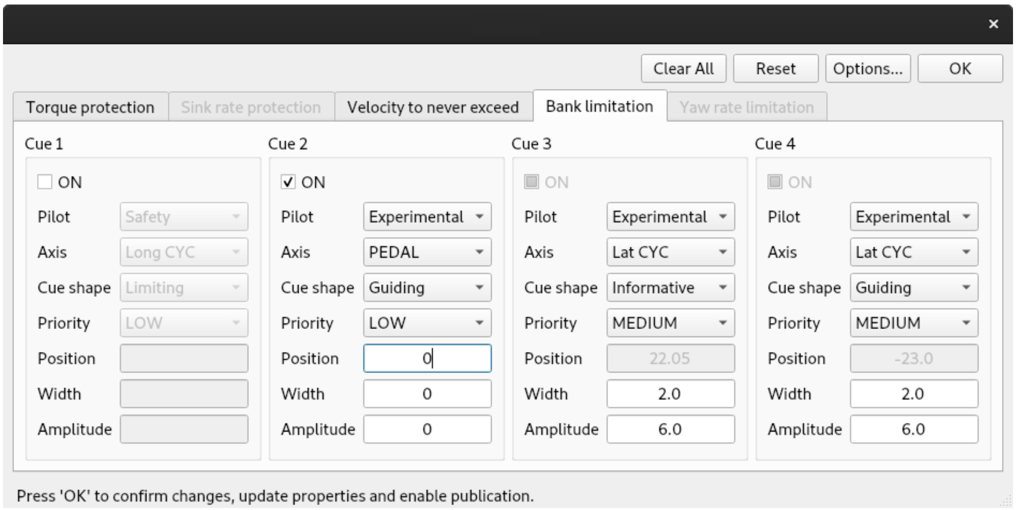


Figure 3.3: Representation of arbitrating module's user interface window

### Input and rule defining sub-module

In general, insertion of a cue through the main interface allows to set the following data:

- *Pilot*: the seat to which current cue has to be referred to. In used simulating environment, two pilot seats are available. Considering an experimental test phase, one of the pilots would have safety-related duties (or in the scenario of a training session, one pilot seat is reserved to the instructor). Pilots definition is particularly remarkable when addressing controls' coupling through the cockpit.

- *Axis*: reference command for the cue. Usually helicopter's control axes consist of: pitch and roll, commanded by longitudinal and lateral motions of the cyclic bar; vertical rate, for the collective lever; and the yaw angle controlled by the pedals (anti-torque). Experimental systems could be provided with additional axes or different configurations.

- *Cue shape*: in order to generalize, three types of cue shapes are provided. User can choose among limiting, guiding and warning types of cue. As instance, it could be considered to assign soft-stops to limiting cues, gates to guiding cues and shakes to warning cues. Final defined cues could then be activated with respect to such classification. The selection of which cue shape is to be filtered is made through the options GUI.

- *Priority*: three levels of priority can be selected for each cue – low, medium, high. Afterwards, through the arbitrating rules the user can select which level of priority to allow and enable.

- *Cue force-displacement data*: basic cue properties allow to specify functions to be added to the stick-force–displacement curve. In case of the soft-stop, which currently is the only available shape for sake of simplicity, main data are represented by start position, end position and amplitude. This set of properties allows to finally construct the segment that has to be added on the force-displacement plot. Therefore, they constitute the instruction that is directly passed to the inceptors' controller block.

As described just above, user may also want to change arbitrating rules or module configuration. Therefore, the options dialog window is provided with such functionality and is a fundamental part of the input and setting task.

Once cues are issued, either directly from the interface or based on an external-running module's signal, inputs concerning the prioritizing law are defined. The routine then processes these data and publishes cues that have been allowed by ruling filter. Specifically, it is possible to refer to a sub-module which, although deeply integrated in the main code, is handling the information of the selected law from the GUI, sending such property to the following parts of the program. It is noteworthy to explain why arbitrating task has been arranged in such a manner.

As aforementioned, there are basically two available possibilities among which to choose, excluding an idle mode. One relies on the cue shape property, while the other on the priority level set for a given cue. The hypothesized scenario in which the program was supposed to be operated would generally consists of conflicting cues triggered during a certain maneuver. Thus, depending on the specific situation, the intention could be:

- To modulate one or more cueing functions acting on the same axis and coming from different sources. For example, two envelope protection cues acting and addressing the same control. In this case one could prefer to set cue classification with respect to the priority level, in such a way that the least critical cue is limited or discard if necessary. Main goal could be to avoid possible confusion with respect to the most important cue. Also one protecting task could be defined with a single main cue that is always active, and other lower prioritized ones which are explicitly called only if there is no risk of situational awareness degradation.

- To modulate one or more cueing functions which have different operational targets. During flight, supposing critical conditions, it could be preferable to neglect cues based on their function. As instance, it could be convenient to switch off or fade out all informative cues, regardless of their priority or axis, to leave space for main envelope protection task. This type of arbitration would be intended to longer time periods. For example, it could be aimed to a sequence of maneuvers or to an emergency condition. This situation could also be concurrent with the previous one. In the latter case, main purpose would be to offer an additional degree of freedom for final cue selection.

**Prioritizing and rule implementing sub-module**

As reported in Figure 3.2, beside a sub-module handling the laws of arbitration, a second integrated routine can be identified which is mainly intended to apply the classification and finally create the instruction for cues to be implemented. Main task for this part of the program is to receive a list of defined cues and, relying on the configuration setting, filter the list and then publish relevant properties. Starting from the data of cues that are set through the interface, first assessment is to sort the list. Hence, a matrix is created with references to the enabled cues allowed by ruling specifications. The matrix contains cue references sorted by control axis. Cues' indications are entered in the matrix only if they follow the rules for priority. This operation constitutes itself the action of arbitration. After the whole list of cues is inspected, matrix is reduced, thus having a number of rows equal to the number of different axes called by the cues, and as many columns as the greatest number of different cues on the same axis. In this way properties from the cues remain stored and are not changed.

Afterwards, a function reads all the references to the prioritized cues contained in the matrix and publishes a relevant message for the cues to be implemented through the appropriate *ROS* node. This function is currently triggered only if the user inserts a cue property's set from the interface and clicks on the relevant button for insertion. In this case, indeed, program resulted to be working efficiently.

For what concerns cues deriving from the envelope protection modules, on the contrary, this method was afterwards skipped. In fact, external modules update their value on the base of a specific frequency. This is in general different and inherent to each one of them, due to construction of the module itself or to a required compatibility with the rest of simulator's apparatus, from which they receive state variables values and messages. Then, maximum update frequency for the arbitrating routine should indeed rely to that of the previous modules. It was found that, to include previously described approach, would have slowed down computational rate. Particularly, it resulted not convenient to create a list, reference it in an arbitrating matrix and then publish all allowed cues. This was mainly due to different required frequency of update related to each module. For this reason, routine was set to publish messages related to external modules every time it received a relevant signal. A multi-threaded process was then arranged to manage different cues independently and follow their inherent working frequency as much as possible. Evidences related to this issue, as is later discussed, were found concerning velocity and torque protections.

# Chapter 4

# Test and evaluation

After development of the prioritizing module and its integration inside the simulator's framework, a test session was planned. The latter was intended to verify functionalities of the cue arbitration module and to investigate about its operation during flight. Particularly, possible detection of changes in the control and situational awareness by the test pilot was addressed. For this reason different test cases were planned, aiming to compare the command behavior and possibly identify situations of improvement.

## 4.1 Test preparation

Test was set up to be conducted in the 2PASD (Dual Pilot Active Sidestick Demonstrator) simulator at the Rotorcraft Division of *DLR*'s Institute of Flight Systems in Braunschweig.

### 4.1.1 Equipment

As described in [12], the laboratory (pictured in Figure 4.1) is equipped with a flight simulator based on a specific model of the helicopter formerly known as *Eurocopter EC-135* – currently re-branded as *Airbus Helicopters H-135*. Simulator's cockpit is provided with two seats, one intended for the safety pilot, the other for the experimental pilot. Main specifications of the simulator are listed below – as also mentioned in [12]:

- Computing and processing framework for simulation and model control.
- $2 \times 5$ active axes inceptors for each pilot station (Control Loading System) provided by Wittenstein, exhibiting features for programmable stick force functions as haptic cueing and axes coupling (electronic rod functionality). System's hardware includes following active inceptors:

Figure 4.1: 2PASD simulator. Photography by courtesy of C. Dullo, *DLR*.

  - Righthand Sidestick (for conventional pitch and roll control)
  - Lefthand Sidestick (for conventional collective or additional yaw control)
  - Pedals (for conventional yaw control)

- A graphic simulation environment with $180° \times 40°$ field of view, granted by $5 \times 55$ inches monitors.

- Flight instruments' panels.

- Operator station. Terminal used to operate simulator interface, control center, envelope protecting modules and arbitrating routine, as well as monitoring and data collection tasks.

In order to evaluate the performance of the cue arbitrating routine inside the control system, flight sessions at the simulator were planned. During such runs, a test pilot would have performed a defined maneuver. Relevant data – beside pilot's feedback – would have been collected for later evaluations.

Part of the test preparation has also regarded an investigation phase on sidesticks installation and simulator interface. The system initially tended to periodically show apparently unpredictable behaviors. A deeper study focusing on the provided software and a limited troubleshooting activity was then conducted. This period also allowed to better understand the potential and the limits of the specific equipment. As a consequence, a testing procedure was defined. Also required

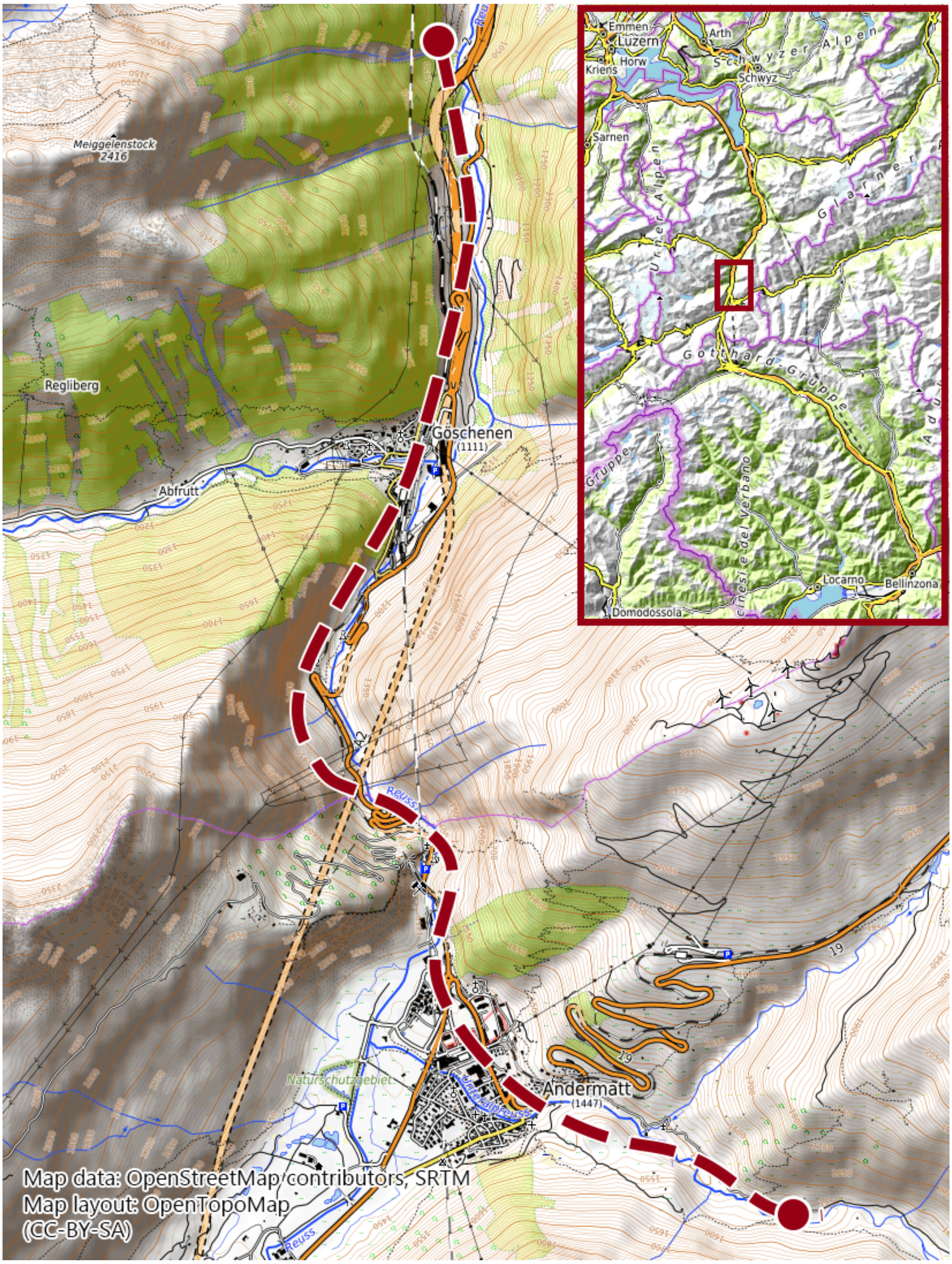


Figure 4.2: Flight setting location and track of planned trajectory (map source [43])

modifications to the cueing and arbitration functions were revealed. Some of these workarounds are further on described.

### 4.1.2 Flight path set

Before the flight, two test pilots were provided with a background history and guidelines for the maneuver. Flight was set in a mountain location, precisely, in the Gotthard massif, between swiss regions of canton of Uri and Ticino, as shown in the upper right frame of Figure 4.2. Such site offered the presence of a narrow and deep valley in the proximity of the St. Gotthard pass which is characterized by particularly steep mountain slopes. During the transfer, an overflight of the villages of Andermatt (1447 m above sea level) and Göschenen (1111 m above sea level) is performed, mainly following the course of the Reuss river in its valley. First part of the flight, instead, follows the course of a tributary, the Unteralpreuss. Within this environment, the mission was set. Expected trajectory was provided with boxes placed inside the graphical scenery to guide flight's pathway. The track of the defined travel runs along the red dashed line in Figure 4.2, from lower end to picture's top.

Flight's background context consisted of a Search and Rescue (SAR) operation, finalized to the transport of a badly injured patient to the closest hospital. Thus the goal for pilots was to perform an intermediate part of this whole figured transfer, in the fastest but at the same time in the safest way possible, following helicopter's envelope protection boundaries. In this way, pilots would acknowledge the situation of emergency and urgency for a mission to be accomplished in a risky condition, such as a near the ground flight.

Entire context was mainly intended to induce the pilot in a condition of awareness with respect to the necessity to exploit controls until envelope's boundaries. In this way, the envelope protection module and, consequently, the arbitration routine, would have been in their range of operation, thus enabling later evaluation. Moreover, trajectory is characterized by a first stage at a moderate velocity, a maneuvered phase with a sequence of narrow curves along mountain slopes and a following acceleration.

### 4.1.3 Test plan and haptic functions setting

The tests were aimed at studying flight activity when multiple cues are active at the same time. These elements allowed to test the system around the following main envelope boundaries:

- Forward True Air Speed limited to a velocity to never exceed of 120 kt (222,24 km/h)
- Maximum torque percent between 63% and 68%

- Bank angle within $-30°$ and $30°$

Therefore, envelope protecting modules provided values for cueing activation to limit or signal the approach of a relevant boundary. Operational target and basic principles leading each haptic function could be figured in several and questionable ways, depending on a lot of different reasons. Within this context, the underlying idea for the available cues to be exploited was the following:

- The haptic function for the velocity to never exceed was meant to have a limiting action, preventing pilots to exceed the boundary.

- Bank limitation was intended to have an informative nature, signaling pilots of a roll angle that is close to the maximum value or slowing a command that would lead to an overcoming.

- Torque protection is a type of limit that the pilot can usually overcome for short period in case of emergency. For this reason it was disposed to have an intermediate role between limiting and informing, basically intended as a guiding or warning threshold on pilot's command.

Specifically, the cue related to velocity to never exceed introduced a softstop on the forward movement of the pitch axis for the cyclic sidestick. Pilots, when approaching and overcoming threshold speed, would feel an increasing counter-acting force that would slightly push against the stick, inducing a nose-up command. Such action translates, in a conventional (with fully articulated rotor) helicopter, in a cyclic blade pitch dynamics – and a consequent flapping motion – that, in simple terms, tilts the thrust vector resulting from the rotor, ultimately decreasing its component along the forward direction. The force to be developed by the pilot to overcome or oppose to this cue was set to a 10 N step. The limitation on roll angle was meant to provide a softstop on the lateral motion of the cyclic sidestick, both for positive and negative deflections. Pilots would than feel an increasing counteracting force when approaching limit roll angle. Being intended to have an informative purpose, this softstop was set to a lower force difference, precisely a 6 N, 2 degrees wide, step. This choice was also motivated by an ergonomic reason, since the force applied on a lateral stroke is generally lower than a push-forward or pull-backward arm motion. Lastly, torque protection consisted of a softstop placed on the upwards direction of the collective lever. Such displacement is also generally favorable for ergonomics and higher forces can by applied. This is one of the reasons why generally force gradient is higher on this inceptor. Softstop was set to provide a 8 N force difference. These values were changed following an initial discussion with pilots. In general it has to be stated that these settings could relatively change with respect to specific pilot's sensitivity, force, intention. Comments from the testing pilots, data about the position of the cues with respect to inceptor's deflection and other functional flight parameters (engine torque, forward velocity, bank angle) were then collected during flight simulations. It is important to notice that all evaluations were carried out for a relatively short travel, therefore there is no sufficient information to consider the effects of higher travel times or heavier overall workloads.

Having available three cue-providing modules, four evaluations were planned, alternatively allowing or disabling cues. Following combinations were tested:

- Torque and bank limitations;
- Velocity and bank limitations;
- Torque and velocity limitations;
- All available protecting cues (torque, velocity and bank) active.

Once the modules were connected to the arbitrating routine, different levels of priority were respectively selected, in order to have these different combinations. The cue computing functions were thus always active, but their actual insertion on the force-displacement curve of the inceptor was alternatively filtered by the arbitration program.

Although these haptic functions primarily act on different decoupled axes, main goal was to evaluate the difference in flight performances when combining their presence and effects in the same maneuver. Specifically, tests aimed at the evaluation of situational awareness for pilots trying to focus on the interaction of different cues rather than the effectiveness of the single haptic function. Hence, main intent was to discern any possible element related to a single function from the perception connected to collective or conflicting behaviors. This assessment was addressed by arranging a series of questionnaires where the perception with respect to both single and simultaneous cues was evaluated. In this way, possible effects related to single haptic function could have been separated and filtered out of global behavior's comments.

## 4.2 Simulator test flight sessions

As previously described, tests were carried out through different test runs. Firstly some runs were spent for the two pilots to learn planned trajectory and familiarize with envelope boundaries, flight instruments, command devices and cueing functions.

After they had practiced the simulation, cueing functions were individually tested. In Figure 4.3, is possible to notice how the three modules specifically work. First plot shows the cue position on the pitch axis compared with the forward velocity. It is possible to see how the softstop moves backward when the threshold velocity is approached or overcome. As noticeable in Figure 4.5, cue position shows

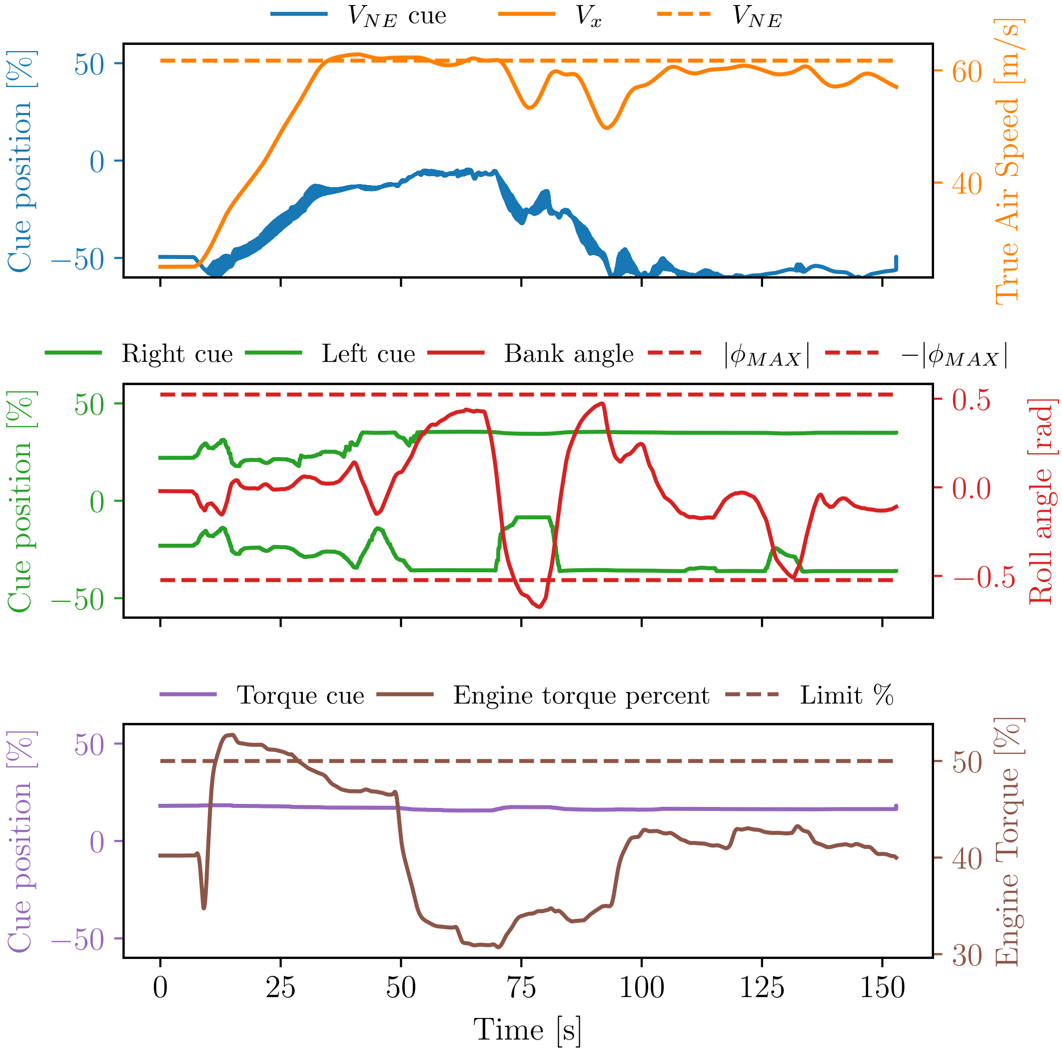


Figure 4.3: Individual cueing functions operational parameters

a number of discontinuities in the second part of the simulation. These segments are known condition and constituted a protection for the module. Original routine ([45]) was indeed based on an inverse model and a PID controller. Simulations showed that, after a narrow turn and a significant deflection on the pedals, that could have quite significantly changed forward component of the speed, program tended to collect a certain delay in the reset process. This behavior led to a possibility to temporarily overcome the velocity to never exceed. On point tests showed a delay of 15 to 20 seconds in softstop recovery and the possibility to gain more than 20 kt beyond the limit. This situation obviously would have degraded haptic function's reliability. For this reason a protection was considered, introducing backup-softstops every time the speed is greater than 125 kt and yet original cue doesn't affect pilot's command. The drawback for such a solution was that these additional softstops would be felt with a rather sudden change in the counteracting force. Pilots then feel an instant impulse that pushes the sidestick backwards and, consequently, the helicopter performs a rapid nose-up maneuver. Pilots were previously informed of this concern and, as they noticed during initial practice, this behavior is hardly acceptable since it could cause unwanted or unpredictable maneuvers. Such feature is then expected to be thoroughly studied, corrected and removed extending original module's approach. However, for the next tests this aspect was accounted as a single haptic function's tendency, thus discerning it from collective evaluations. Moreover, interaction of velocity protection with other modules mostly appeared during first half of the flight where module was operating as reliably as expected.

Second plot in Figure 4.3 shows bank limitation cues related to the roll angle. Softstops related to this function were limited to a position of $+7.5°$ and $-7.5°$ of the cyclic sidestick lateral deflection. This aspect was a modification to the original module that allowed to avoid unpredictable divergent displacement of the softstops. It has to be noted also how the plotted coordinates for softstops are defined by their starting position. That is the reason why a discrepancy is actually present in the left and right values. Accounting for softstop's wodth, haptic functions' symmetry would be attained. However, it is noteworthy to see how, accordingly to a variation of the bank angle, corresponding cue tends to close in and, indirectly, slow down the rolling rate command. On the contrary, the side that is not affected from the current deflection of the sidestick tends to bring its value back to the original value. Lastly, the softstop related to the torque is reported comparing it to collective sidestick's deflection. This function was originally built using a very stable and robust model, therefore also the cue position is rather constant.

At the end of these evaluations, pilots were asked about comments on the perception of each haptic module. The questions related to each one of then were discussed in detail as above described. This feedback was also used to find possible improvements and consider further developments of the program.

## Test case 1

First test case saw the haptic functions related to the enabled torque and bank angle limitations. As visible in Figure 4.4 these cues were simultaneously active in different occasions during flight, mainly in the first part. Comments about the interaction of the two functions outlined how, basically, there is no significant sign of potential conflict as the commanded axes can be considered independent. It can be deduced that the quality of pilot's reception for what concerns separated inceptors is probably only to be ascribed to the individual cue property and operation. This appears to be especially true when cues targets are rather disconnected also on

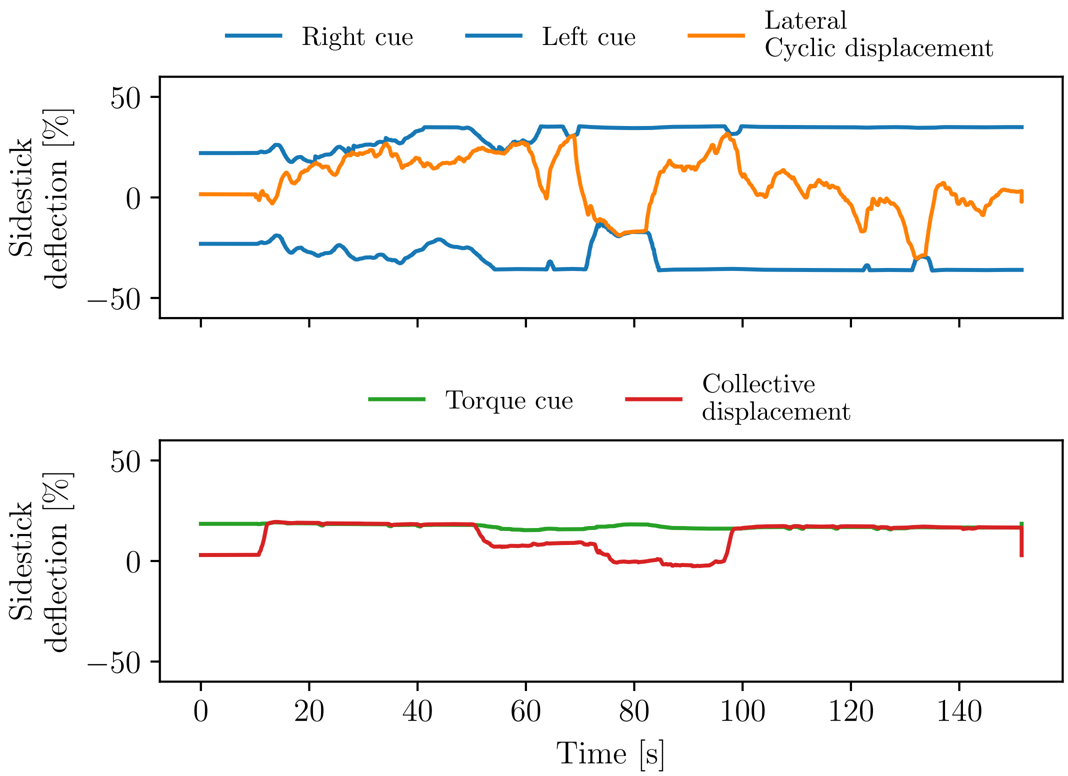


Figure 4.4: Prioritization of bank and torque cueing functions

the flight control level. To simplify the concept, tests didn't require a maneuver that would have directly involved these two commands, but more likely they were controlled and activated separately along the trajectory. Even if sidesticks were located around softstops at the same time, force gaps were received as two different information by the pilot. This situation could be considered a positive operative condition, as long as pilot's awareness is kept constant for both cues, without risking of neglecting one of them. The possibility for the pilot to almost unconsciously lay the command stationary at softstop threshold and lose focus on one of the cues should be more thoroughly evaluated, more appropriately in the context of longer periods' flights and continuous workloads, as well as in addition to a trim feature.

## Test case 2

Second evaluation with multiple cues active concerned velocity and bank limitations. During the maneuver, as predictable from the trajectory plan in Figure 4.2, pilots were expected to perform an initial – relatively wide – right turn and, afterwards, a rather rapid alternation between a couple of left and right narrow turns.

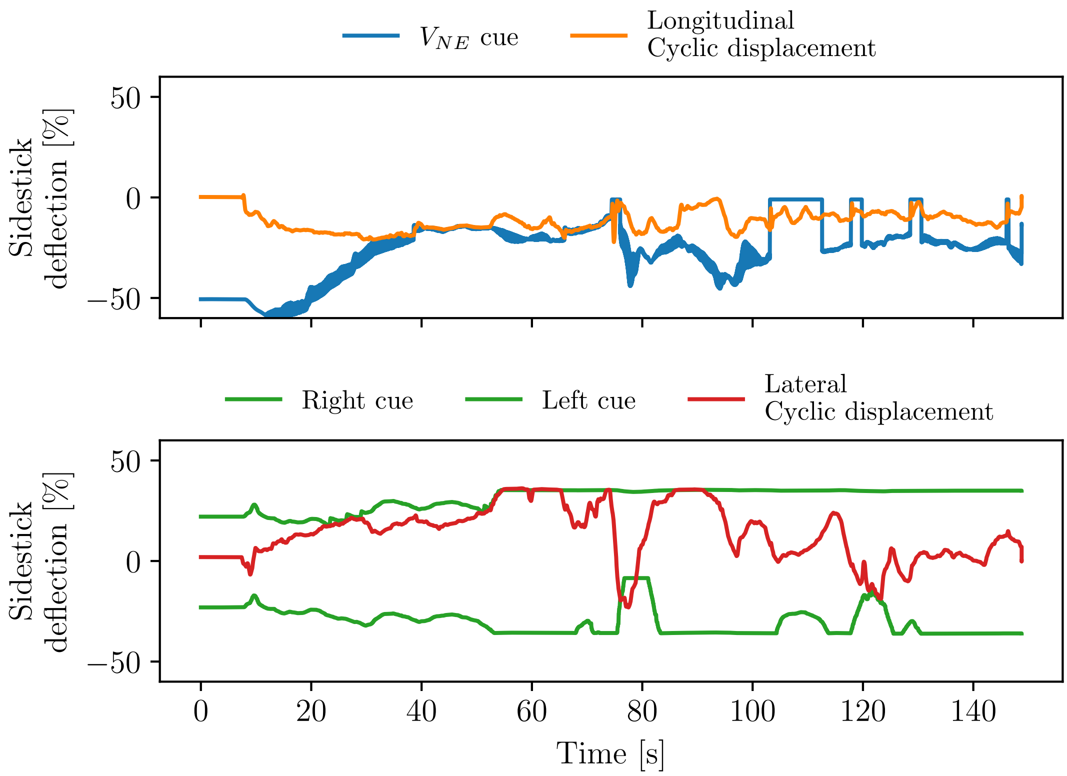


Figure 4.5: Prioritization of velocity and bank cueing functions

Before these two turns, helicopter was taken to a higher velocity due to the context of a SAR mission. At the end of acceleration to $V_{NE}$, and in proximity of the turns, the two cues were then likely to be simultaneously perceivable for the pilot. This situation was actually recognized by the pilots during the tests as noticeable from the answers to relevant questionnaires. It is also visible from Figure 4.4 how in the interval between 35 and 75 seconds of the simulation the cyclic sidestick lies, for both directions in the range of the cueing function. Particularly, velocity cue limits the command that, for some instants of the maneuver, lies in touch with the softstop. Meanwhile, the lateral cue is involved in a more sporadic way. Occasionally this command also overcomes its relevant force step. This behavior was suggested by the pilots, preferring a change to the original configuration. The amplitude for the lateral softstop was decreased indeed with respect to the one in the forward direction. Such modification allowed a better maneuverability in narrow turns. Longitudinal cue (for which the negative displacement is implying a forward deflection) was set with a relatively high force gradient to prevent pilots to easily overcome it. To use same configuration also for the lateral haptic function would have meant for pilots to see their maneuvering capability significantly limited. This situation should be avoided mainly for the bank cueing function which was expected to have more of an informative purpose. After the modification pilots found the presence of the two cues to be acceptable and globally not conflicting.

## Test case 3

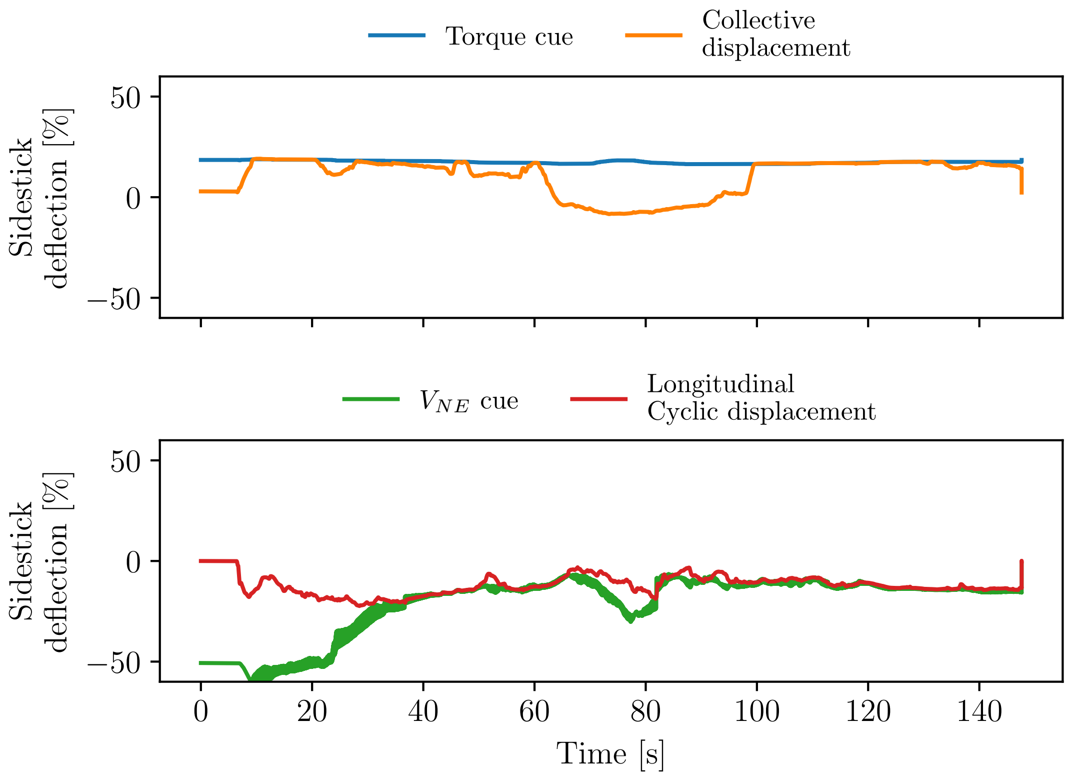


Figure 4.6: Prioritization of torque and velocity cueing functions

This flight test run was conducted with velocity and torque modules activating cues on their relevant axes. This session saw the two cues being often involved, also simultaneously. Specifically, Figure 4.6 reveals how they were quite extensively exploited at the beginning and at the end of the travel. These two parts of the trajectory basically offered indeed a forward acceleration with a slightly sloped climb. Also, as for the first test, no substantial conflict was perceived by the pilots, for the fact that the cues were active on different inceptors. In this case though, relative modulation of softstop's amplitude played a more remarkable role. Specifically during climb, a stronger cue on both axes could limit pilot's authority and maneuvering possibility. A more gradual haptic function, as instance on the torque protecting cue, could help letting pilots have a higher level of control.

## Test case 4

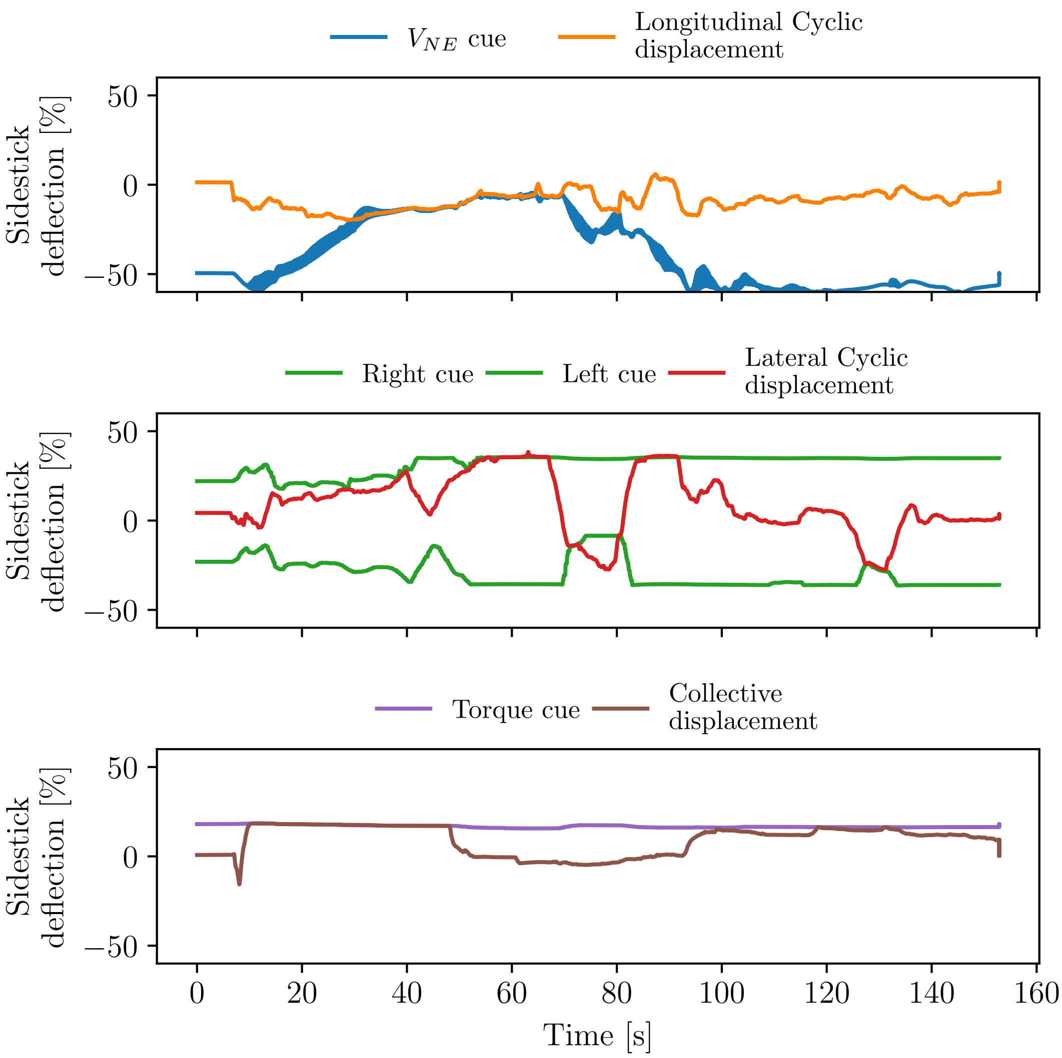


Figure 4.7: Evaluation of conflicts for all cueing functions active

Last test case was carried out activating all the three cueing functions. As noticeable from Figure 4.7, during some short moments of the flight, the three involved commands were all in proximity of their relevant cue. A comparison with the previous cases was then possible. Pilot's comments mainly focused on the possibility to modulate the amplitudes of the softstops. No remarkable conflict was detected, but, to better perform the maneuver, a different approach for each of the haptic function could be arranged. This remark also suggests to not only give different types of priority to the cues but also differentiate their feeling intrusiveness.

For example, a limiting cue – as the velocity protection was herein intended – could have a larger force gradient, while a guiding haptic function – as the torque was intended – could likely have a more gradual force gradient. More complex cue shapes could in this case be used, as for instance consecutive softstops with increasing gradient. This approach would provide the pilot with a possibility to more easily act on one axis in the case two or more envelope boundaries are being approached. This effect was partially attained with the bank limitation, but a deeper investigation would still be required.

Lastly, an observation about update rate should be reported. It was found out that the original frequency of communication between torque protection module and control loading system was too high for the sidestick's motor to update the cue properties as received through the *ROS* framework. For this reason, initially the relevant haptic function locked up on a constant definition, making it impossible to reset the stick's force-displacement characteristic. A workaround for this problem was to lower the updating and messaging frequency to a last acceptable value. However, it is desirable for future developments to more thoroughly investigate on such evidence, optimizing and tuning operative and updating frequencies. A similar issue also arose with the arbitrating routine performance. As previously mentioned, program works on different threads, since, initially, computational speed was too low with respect to the other modules of the framework. This condition resulted in a slower rate of update and output communication. Optimizing the code workflow and limiting torque protection's rate of update, the overall performance was improved to acceptable values. Still a complete evaluation of computational performances and processing rates should be carried out, and especially if the system's complexity is increased, such assessment would likely become a requirement.

# Chapter 5

# Conclusion

After simulator flight tests, it was possible to collect comments from pilots and to examine data recordings from the different runs. It was then possible to have a more complete overview, with some observations, hypothesis and open points. Before drawing main remarks, it is noteworthy to outline once more that active inceptors, from the perspective of the work described in this essay, have a significant number of potential opportunities and features that can be arranged to enhance piloting activity. This characteristic was surely confirmed while actually operating the system. That being stated, first assessment regarded the investigation on specific system, getting to know characteristics, procedures and protocols, preparing software for following tests. Development of the arbitrating module and the adaptation of the cueing functions followed suit.

As noticed during the tests, first evidence would be that global behavior of the cueing feature is strictly connected to the performance of the single haptic functions. It became evident that if one of the cueing modules is not sufficiently reliable or accurate, the whole tactile information's perception by the pilot is significantly degraded. Once that individual modules are operated effectively, arbitration can take place. The condition of simultaneous and possibly conflicting cues was then investigated. It emerged that a modulation of one of more cues could help the pilot perform the maneuver especially when the haptic functions involve the same inceptor. In this situation it would be desirable to arrange the cues to different levels of priority and set softstops properties according to such classification. In this way it was observed how pilot could handle the envelope protection with a better authority and ability to control the maneuver. Particularly, when the bank limitation and velocity to never exceed cue were active, it was suggested to lower the force gradient for the roll command (which was set to lower priority). In such a way, pilots could hold forward deflection while still have a good degree of freedom for sidestick's lateral displacement. This effect had lower relevance when the cues were simultaneously active on different inceptors (as instance, one cue on the collective sidestick and the other on the cyclic sidestick). Yet, also in this case, it was suggested to classify the haptic functions in order to differentiate the feedback. Softstops' definition should also be modulated to avoid induced and momentary command's position-hold.

In general, it can be concluded that an arbitration of the cues is well received by pilots because makes the haptic functions more understandable and compatible when acting at the same time. An extension of this concept could be to study an adapting arbitrating modules that changes its settings accordingly to flight parameters. This modification could easily be implemented on the proposed arbitrating module. As instance, comments from pilots also suggested a change in the bank limitation with the possibility to make it more restrictive at lower speeds and in hover, rather than at higher speed. It could be then interesting to monitor flight parameters like the velocity, for cues' prioritization (for example, torque and bank limitations). This could lead to modulate softstops' amplitudes with respect to the speed. Instead of implementing such relations within each one of the modules, this insertion could be directly applied by the arbitrating module. As for the routine proposed in previous chapters, protecting modules would then only provide the position of the softstops. Meanwhile, a general and integrated program would process these information, filtering and regulating them before sending cueing shapes to the control loading system. Hence, further activities could see an enhancement of the current environment, with the possibility to change the arbitrating rules with respect to the flight condition's parameters or following the detection of a specific maneuver.

Two additional improvements can be foreseen after the tests. First one relies on the development of other cueing functions. With the insertion of additional envelope protections, arbitrating module could even be exploited to handle different cues acting, not only on the same inceptor, but also on the same axes. It could be interesting to evaluate pilots reception, in this case.

Second possible evolution of the system could be expanding the use of different cueing shapes, like gates or detents, on the sidestick's force-displacement curve. As the AIS already provides such possibility, it appears again more convenient to have a single and central interface to handle cueing functions' specifications. A separate routine would only receive coordinates' information from the external modules for cues to be implemented.

Lastly, an evaluation on longer flight sessions would be required, as effects of force gradients were only analyzed for relatively short runs. In this context, the trim function should initially be implemented for the operated system. Afterwards, it could result interesting to study operation of arbitrating module in longer runs. The possibility to change module's parameters as a function of pilot's estimated workload could also lead to significant remarks. Consequently, operation of the haptic shapes should be investigated in the perspective of activation of trim function.

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