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OPERATOR-CENTERED & MODEL-BASED DESIGN FOR CRITICAL HMIS: APPLICATION TO THE NEW CSG OPERATIONS CENTER FOR REUSABLE LAUNCHERS

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1 INTRODUCTION

Designing usable Human-Machine Interfaces (HMIs) is a complex activity involving multiple stakeholders with potentially conflicting objectives. ISO 9241 part 11 [1] defines the usability property (composed of contributing factors called efficiency, effectiveness and satisfaction) while ISO 9241 part 210 [2] defines the User Centered Design process which makes explicit involvement of end-users in the various development phases (needs analysis, design, evaluation, ...). Unfortunately, these standards mainly focus on simple, walk-up and use systems such as mobile apps.

HMIs deployed in critical contexts (such as launcher control centres) present specific differences with respect to the walk-up and use systems including but not limited to:

- the impact of a failure of the HMI as well as of the operator may have catastrophic consequences
- the operators' work may be complex requiring high levels of concentration as well as specific competences and skills
- the operators work as a team (of various sizes) that need to collaborate efficiently in order to reach the missions' goals, ...).

These differences call for specific processes and tools to guarantee the presence of specific properties such as usability, operability and learnability.

This paper presents a model-based process to design and evaluate critical HMIs. The models, which include a task model capturing the work that each operator has to perform as well as the cooperation between operators (and its applicability to satellite ground segments), have been demonstrated in [3] and [14]. Beyond, this task notation (detailed in [5]) integrates concepts such as knowledge and skills (to be mastered by operators) and thus supports analysis of learnability and assessment of training needs as demonstrated in [13]. Demonstrating the correct behaviour of the HMI and the underlying system (using formal approaches (e.g. in [9]) or fault tolerance mechanisms dedicated to the HMI (e.g. in [11]) is also of prime importance, but is beyond the scope of this paper.

The paper is structured as follows. Section 2 presents generic Operator-Centered development process used for the design of the HMIs. Section 3 presents the application of some parts of the process on the new Operations Centre (CDO) at the Guiana Space Centre (CSG) being developed for increasing flexibility of the launch base. The CDO will open the launch base to new launchers. Section 4 focusses on CALLISTO launch operations, which presents the specificities of being able to exploit and manage reusable launchers. This section presents multiple HMIs developed in order to favour different and conflicting properties such as usability (and more precisely efficiency) or similarity [12] with available already deployed HMIs. Section 5 concludes the paper.

2 A GENERIC DEVELOPMENT PROCESS FOR CRITICAL SYSTEMS

In critical contexts, effectiveness and efficiency to accomplish user tasks are very important but there are additional constraints to be accounted for on the system being used such as reliability and operability. Additionally, beyond these constraints on the final products, constraints also apply to the development process itself. Furthermore, operators of such systems are trained to use the system, being required to follow operational procedures and behaving in an appropriate way according to both safety regulations and mission constraints. We thus used a development process that addresses interactive systems issues, safety critical concerns in system development as well as human factors issues.

2.1 Overview of the generic development process

We used the process named "Development Process for Usable Large Scale Interactive Critical Systems" introduced in [4]. This process leverages informal HCI techniques (including mock-ups, low-fidelity prototyping, field studies...) and formal HCI techniques (including formal description techniques, formal analysis, performance evaluation...) to address usability, reliability and operability properties that generally not targeted simultaneously. Fig. 1 presents an abstract view of an

iterative development process for critical interactive applications. As stated in the introduction, the models make explicit the design and construction of a training program and the required iterative aspect (dotted arrows) for addressing users' needs and required changes following a usability evaluation.

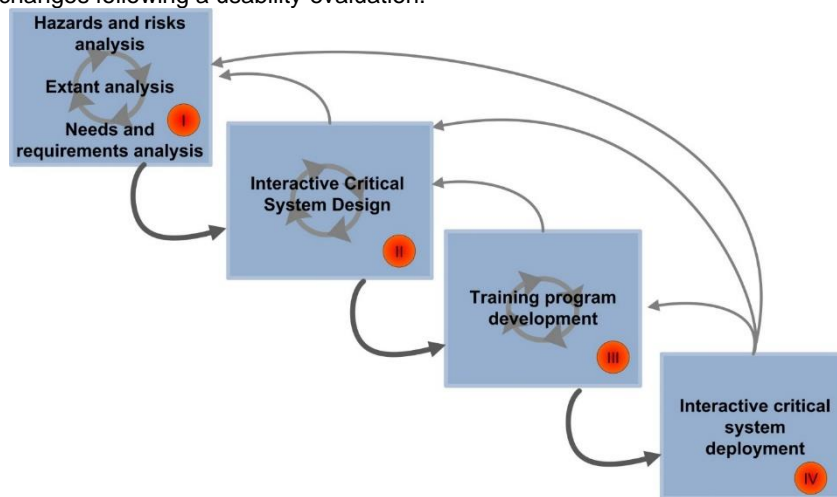


Fig. 1. Overview of the generic development process for critical systems

2.2 Focus on the consistency between operators' tasks and HMI

Fig. 2 presents a more detailed view of this development process making explicit the three specific sub-phases of the interactive critical system design process:

- Task analysis and modelling phase (under discs 3 and 7),
- Low-fidelity prototyping iterative phase (loop represented by discs 2, 3 4 and 5),
- Very-high fidelity prototyping iterative phase (loop represented by discs 6, 7, 8, 9 and 10).

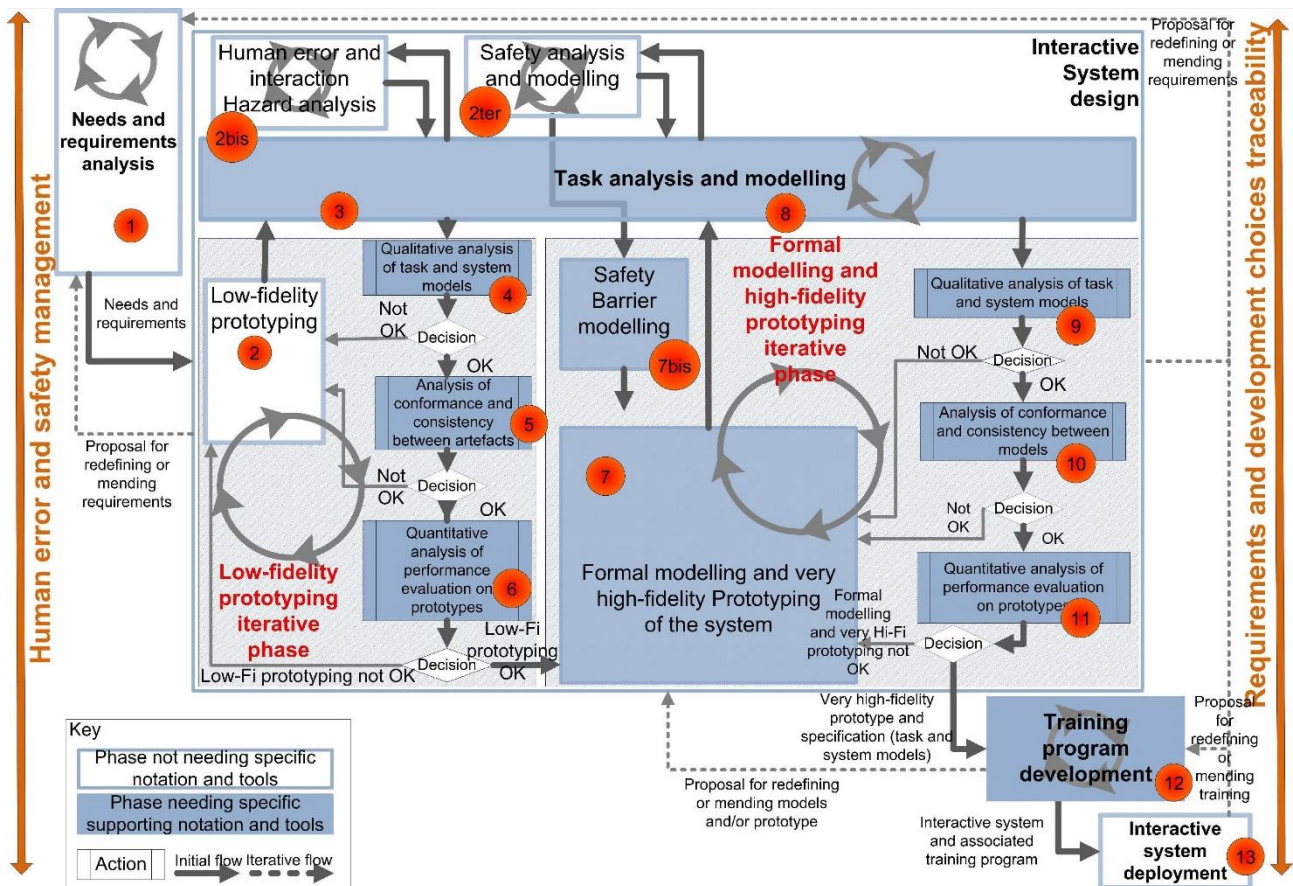


Fig. 2. Detailed view of the generic development process for critical systems

In this article, we focus on the two first specific sub-phases: task analysis and modelling, and low-fidelity prototyping iterative phase. These two aspects are presented in section 4. Safety aspects are also of prime importance (especially to prevent damage to the population in the vicinities of the launch pad) but this is beyond the scope of the paper.

Task analysis and task modelling (discs 3 and 8 in Fig. 2) aim at understanding and describing operator activities. This key step in the process enables to ensure that:

- The HMI provides the complete set of necessary functionalities to support operator activities (related to the effectiveness property of the usability factor),
- The operator will be able to accomplish their goals in an acceptable timeframe while using the system (related to the efficiency property of the usability factor).

Task modelling highly supports the design of a usable interactive system as it enables to precisely identify goals, tasks and activities that have to be carried out by the operator. Task models bring additional advantages to task analysis: the structuration of the gathered, regarding operator activities and the possibility to use software tools to compute, analyse and simulate these models.

The low-fidelity prototyping iterative phase (discs 2, 3, 4, 5 and 6 in Fig. 2) aims at preparing initial versions of the interactive system and enables the evaluation of first design outcomes without engaging too much human and financial resources at this stage of the process.

High-fidelity prototype (disc 7) would be performed using a combination of formal methods and standard programming techniques depending on the required level of dependability of the final system [10].

3 CASE STUDY

3.1 The Guiana Space Centre, Europe's Spaceport

Founded in 1964, the Guiana Space Centre, Europe's Spaceport, is facing a rapidly evolving environment. These evolutions concern several aspects of our activities and take place in three phases:

- Short term: Arrival of new launchers ARIANE6, VEGA-C.
- Medium term : partially reusable launchers.
- Medium / long term : "micro-launcher" type systems to meet the needs of "mini" and "micro-satellite" missions.

The Guiana Space Centre must also reduce maintenance and operating costs for all users of the launch base, whilst at the same time respond to the needs for improved flexibility and a reduction in shorten operational cycles.

3.2 Towards a new Spaceport

Since 2017, CNES and ESA management have been working together to define the concepts for a New Generation of the Core Launch Range. The program, known as the CLRR (Core Launch Range Renewal), or CSG-NG in French. The CLRR aims for a gradual modernization of the launch support system (managed by CNES), initially covering investments that should contribute to:

- improving operational efficiency
- introducing new working methods
- greater flexibility and modernization of the base
- increased use of remote control and monitoring capabilities
- replacement of end-of-life equipment

With of course, a main objective of cost reduction during operations and maintenance. This objective requires fundamental restructuring of the Spaceport's operational concepts. These new operational concepts can only be implemented using investments for dedicated & new infrastructures. Once in place, enforced operator training is planned, for training personnel in these new operational concepts.

One of the main priorities of the CLRR program, is the construction of a new operations centre, the CDO ("Centre des Opérations"). With its new ground system architecture, the CDO brings the capacity to manage several launch campaigns in parallel. The CDO also promises to reduce the delay in preparing for a new launch, thus reducing costs.

3.3 The CDO: a new operations centre

At the Guiana Space Centre, a new operations centre, the CDO, is being developed providing a flexible and open spaceport for existing and upcoming launchers. The new operations centre, the CDO, aims to enhance capabilities of the Core Launch Range by:

- centralizing operations that are currently distributed across 12 technical buildings
- fostering the automation and the remote operability and maintainability of its resources
- managing multiple launch campaign configurations in parallel

The expected benefits include:

- increased operational capacity for the CSG by parallelizing multiple operations
- flexibility, with quick and safe system reconfiguration
- rationalization and optimization of processes and operations
- decreased energy consumption

- enhanced training & validation of systems via a digital simulator

The new operations centre is profoundly renewing all Core Launch Range systems and services, including all the IT and the operational equipment that is necessary to support the execution of the launch campaigns. Examples include: launcher data telemetry acquisition and processing & launcher tracking to determine a real time launcher trajectory for safety purposes, weather forecasting & telecommunications ...

This presentation focus into the architecture and the functions of the CDO, but also shows how the new operational concepts are being developed and how the business and the organization will have to evolve and change and what new skills need to be implemented. The new operations centre, the CDO, has been designed to enhance the core launch range support operation capabilities detailed [6]. The main functions of the CDO are detailed in Fig. 3.

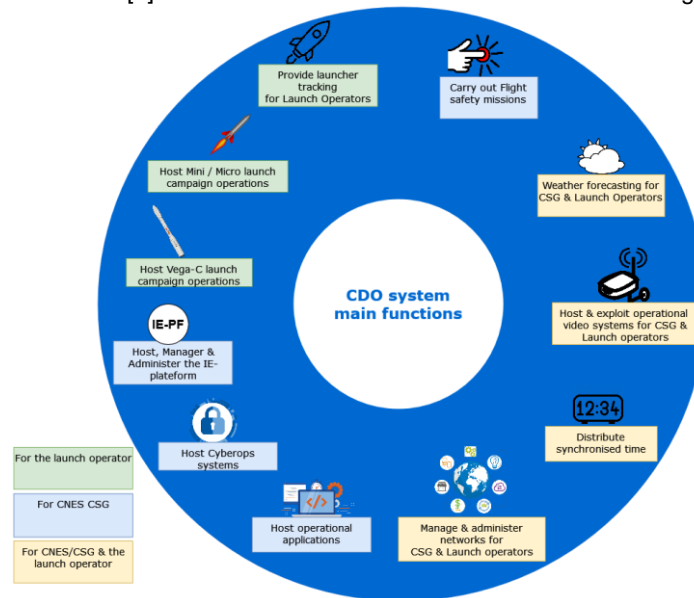


Fig. 3. CDO system main functions

4 THE CALLISTO LAUNCHER - NEW OPERATIONAL CONCEPTS

With the arrival of reusable launchers, such as CALLISTO, operational concepts and in particular, Flight Safety operations are changing. At the CSG, Europe's Spaceport, studies are currently taking place in order to anticipate the impacts on the Flight Safety Officer (FSO) missions and work, in order to provide “usable-by construction” & “learnable-by construction” Human Machine Interface design.

CALLISTO (Cooperative Action Leading to Launcher Innovation in Stage Toss-back Operations) is a reusable vertical take-off / vertical landing rocket first stage demonstrator, propelled by rocket engine and developed jointly by the German Aerospace Center (DLR), the French Space Agency (CNES), and the Japanese Aerospace Exploration Agency (JAXA). The CALLISTO project brings new constraints on the FSO HMI including very short reaction time to manage potential deviations and high impact decision-making on vehicle neutralization in case of unacceptable trajectory deviations.

This paper demonstrates how a hardware and software HMI has been designed in order to address all of the above challenges including assessment of workload and ensuring operator performance.

4.1 Adapting the HMI, now and for the new CDO

CALLISTO is scheduled to take off and land from the CSG by the end of 2024, before the arrival of the CDO and its new available HMI. Therefore, the baseline is to adapt the current Flight Safety HMI by implementing the changes necessary to guarantee the feasibility and operability of the flight safety mission while minimizing the risks of failure.

Firstly, a requirement analysis was conducted by dynamically modelling the behaviour of the launcher during the course of a nominal trajectory as well as a deviation (see acknowledgements). Thanks to the modelling, the team of flight safety engineers was able to visualize the dynamic behaviour of the launcher together with the authorized flight corridor. Both the feedback from the flight safety engineers as well as the dynamic models were inputs to the HMI design process that followed.

The design process consisted in three iterations. During each iteration, three versions of the HMI were presented to experienced flight safety engineers: one low cost / minimum modifications version, one version using the minimum necessary data and one intermediate version. The feedback from the engineers was taken into account for the following iteration, which was presented to other experienced flight safety engineers, in order to obtain unbiased feedback at each iteration loop. Furthermore, with each iteration, the HMIs gained in fidelity.

Because of the CALLISTO launcher characteristics and its trajectory, the reaction time at the summit of its trajectory is very short. This phase was therefore the main focus of the design process. Specific features were added and optimized to help the Flight Safety Operator better anticipate the arrival of this critical phase and also help them with their mission in case of trajectory deviation. Given the short reaction time, computer-aided decision-making features were also integrated in the different versions. Furthermore, because of the vertical profile of the trajectory, it is impossible to define a static flight corridor for the whole flight. Therefore, the authorized flight corridor will vary with the altitude of the launcher, which is a major change with respect to the currently operated launchers. This particularity was introduced in the models displaying the dynamic behaviour of the launcher and assessed during CALLISTO's HMI study. As a result of this design process, the modifications to the current Flight Safety Team HMI are presently being specified and their implementation on CSG's operational system is scheduled for 2023.

4.2 Presentation of the HMIs and their associated task models

In this section, each HMI version is presented, accompanied by the task model presenting how the HMI is meant to be used by the Flight Safety Operator. The task models are created using the HAMSTERS notation (see Fig. 4 for a very brief presentation of the icons). The HAMSTERS tool is available here [5]. The models present all the different tasks that the Flight Safety Team operators have to perform concurrently in order to track the launcher's trajectory and detect a potential deviation from the nominal computed and expected trajectory. The task models produced in the project are detailed and thus very complex. Due to space constraints this paper only presents simplified versions relating to the monitoring of the launcher's trajectory. The different types of tasks analysed are (see Fig. 4):

- abstract tasks: tasks used to represent a group of tasks;
- interactive output tasks: tasks that highlight the interaction between the operator and the output of the system;
- system tasks: they represent actions performed by the system which interfere with operators' activities;
- perceptive tasks: tasks that the system operators do by using their senses. In this case, the most recurrent perceptive task is the "sight perceptive task" in order to perceive an information displayed;
- cognitive tasks: tasks that indicate how the operator treats information (for example by analysing it or by taking a decision according to the information analysis).










Task type	Icons in HAMSTERS task model
Abstract task	 Abstract task
System task	 System Task
User task	    User Task Perceptive Task Cognitive Task Motor Task
Interactive task	   Interactive Input Task Interactive Output Task Interactive input output task

Fig. 4. High-level task types in HAMSTERS

These tasks are connected by symbols called "operators" which represent the temporal ordering of the tasks. For instance, a "sequence operator" (symbol ">>") makes explicit the fact that the group of tasks it connects must be executed one after the other. The "concurrency operator" (symbol "|||") makes explicit the fact that the connected tasks may be performed by the operator in any order.

First HMI

The first version of the CALLISTO HMI, presented in Fig. 5, is a transposition of the current system that the Flight Safety Team uses to monitor all of the launchers at the Guiana Space Centre. Minimum changes were performed to reduce as much as possible the costs that modifications could have and favour the similarity property [12].

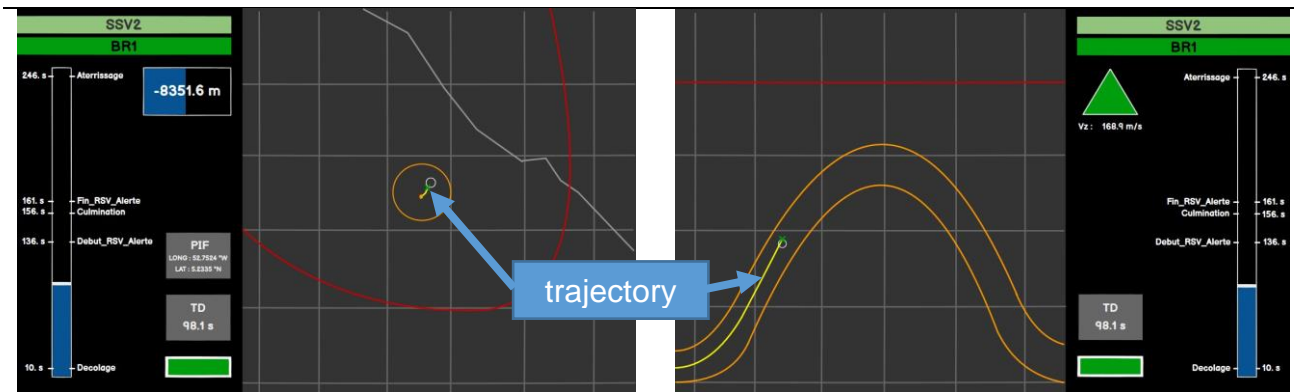


Fig. 5. First version of the HMI for CALLISTO (left side the horizontality representation – right side the verticality representation)

The HMI is composed of two different screens displaying the trajectory of the launcher, which implies two different points of focus for the Flight Safety operator. The left screen aims to show the horizontal position of the launcher in terms of longitude and latitude while the right one displays the verticality position of the launcher in terms of altitude and time. The information displayed on these screens is rich and the main parts exploited by the operator to monitor the launcher are the two trajectories (at the end of the arrows in Fig. 5).

In both graphs, the operator has to observe the following information:

- the current position of the launcher (left screen) and the current altitude of the launcher (right screen) are showed through a green cursor displayed as a cross on the screens;
- the nominal position of the launcher (left screen) and the nominal altitude of the launcher (right screen), which corresponds to the precalculated position and altitude of the launcher at a given time « t », are displayed by a white cursor with a circle shape;
- the alert limits, represented by orange lines in both screens, allows operators assessing whether or not the flight is nominal. If the cross representing the current position of the launcher is located outside the limits, the trajectory is considered off-nominal.;
- the authorised flight corridor, represented by red lines. show the zones in which the operators need to react promptly (possibly by neutralizing the launcher).

For the purpose of ensuring the protection of the population, the environment and goods, the operator has to be fully aware of this information continuously to detect as promptly as possible a launcher’s trajectory deviation.

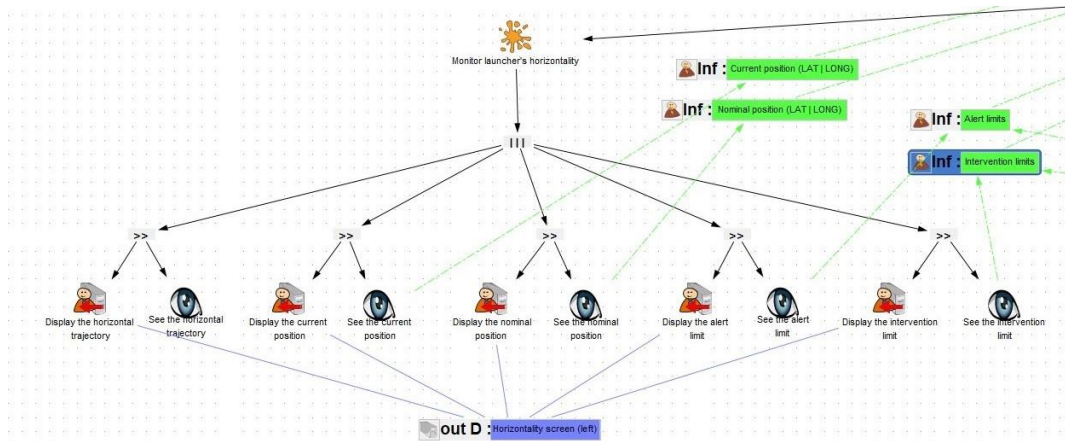


Fig. 6. Task model for the monitoring of the horizontal launcher’s trajectory of the first HMI (see Fig. 5)

The task model, in Fig. 6, corresponds to the tasks the CALLISTO operator needs to do (using only the left screen) in order to monitor the horizontality of the launcher’s trajectory. A similar pattern is used for each task where the system presents information to the operator (interactive output task) immediately followed by the perception of this information by the operator (perceptive task).

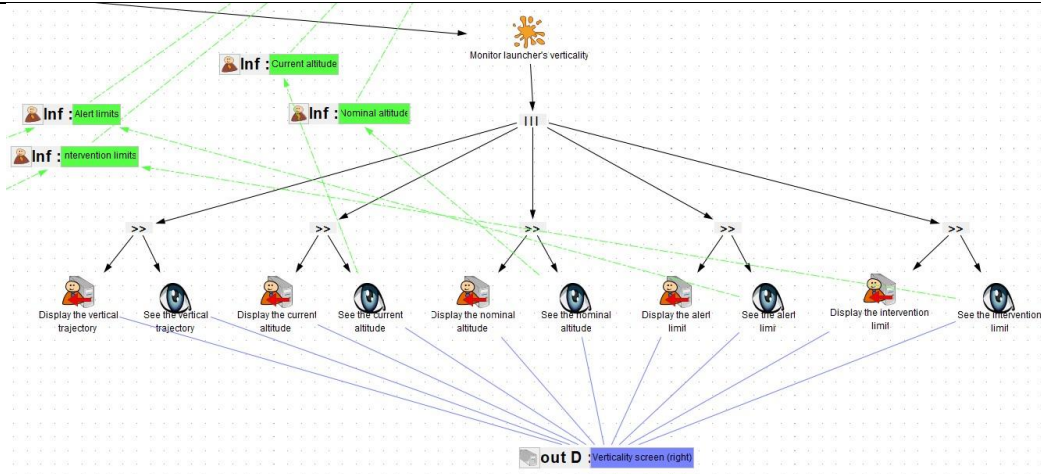


Fig. 7. Task model for the monitoring of the vertical launcher's trajectory of the first HMI (see Fig. 5)

Similarly, the task model in Fig. 7 serves as a representation of what the CALLISTO operator has to do to monitor the verticality of launcher's trajectory. The global structure of the task tree is identical to the previous one, only the information displayed and the screen on which the information is presented, changes. For instance, the system outputs the current altitude to the operator (interactive output task) and the operator must perceive this information (perceptive task). The operator has to repeat this process for every information displayed on the screens related to the monitoring of the launcher's trajectory. Once the gathering of the information has been completed, the information is analysed (cognitive task) in order to decide (cognitive task) if the launcher may be deviating from nominal trajectory. The analysis of the operator tasks with the first HMI version of the system (concerning the monitoring of the trajectory of the launcher) shows that the operator has to do a huge number of concurrent tasks. In addition, the operator has to shift their focus between two different points of interest, between the horizontality (left HMI from Fig. 5 and task model in Fig. 6) and the verticality of the launcher (right HMI from Fig. 5 and task model of Fig. 7).

Second HMI

The second HMI, presented in Fig. 8, corresponds to a second version of prototype in the iterative process of Fig. 2. Its main objective is to reduce the perceptive and cognitive load of operators by grouping, in a single screen, all the information that the operator needs to monitor the launcher. By gathering all the information on a single screen, critical information does not need to be duplicated on two screens (for example, displaying the start time of the operations).

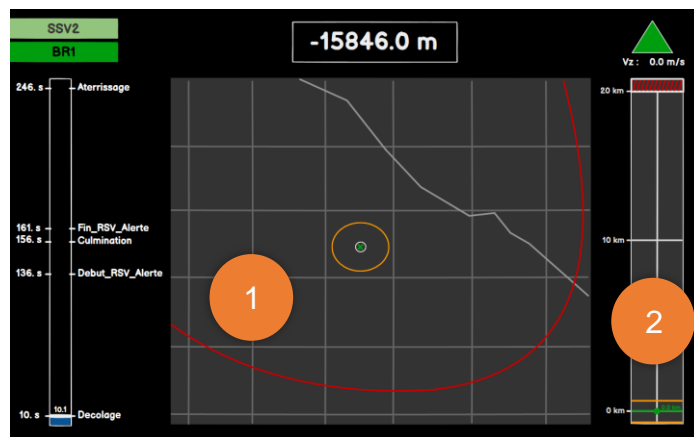


Fig. 8. Second version of the CALLISTO HMI, blending on a single display (verticality and horizontality screens) of the first HMI

On the second HMI version, the verticality screen is replaced by a bar graph (disc 2 on the right-hand side of Fig. 8) that reflects the real time altitude of the launcher, the limits of alert and the authorised flight corridor in verticality. The nominal altitude of the launcher has been suppressed (following interviews with the Flight Safety team) in order to reduce the information load while taking into account the important reduction of display space. As with for the first HMI, this HMI features two main focus points: the graph representing the horizontal trajectory of the launcher (disc 1 in Fig. 8) and the bar graph of altitude (disc 2 in of Fig. 8). The grouping of all the information in one single screen significantly reduces the quantity of eye movements thus improving efficiency during the monitoring tasks. By gathering all the information together, the new HMI reduces memorization needs with respect to the first one. For instance, the vertical limit of alert is only represented on the verticality window (horizontal red line on the right screenshot in Fig. 5 is). If the operators' needs this information while looking at the left screen, they have to remember it or to check it again by looking at the right screen.

Third HMI

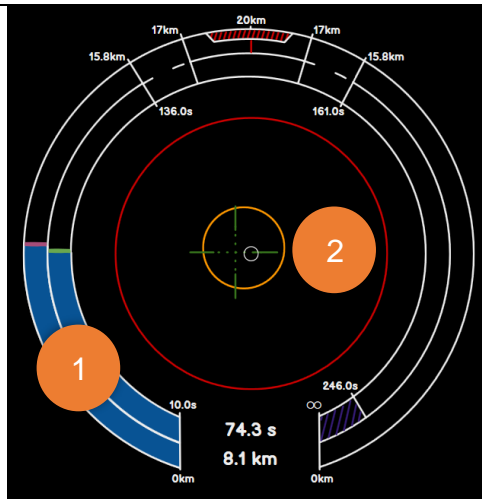


Fig. 9. Third version of the CALLISTO HMI, blending all the information with a single focus point on trajectory to assess potential deviation

The third version of the HMI, presented in Fig. 9, aims to remove the two focus points in the second HMI. The bar graph of altitude has been replaced by a circular progress bar (disc 1 in Fig. 9) which surrounds the horizontality graph of the launcher (disc 2 in Fig. 9). By this means, the focus of attention of the operator takes place in a reduced space. This limited area contains the most important information :

- the current altitude, represented by a pink cursor on the outer circular progress bar (see left side of Fig. 9),
- the vertical alert limit, shown by the white lines related to the “15.8km” text (see top of Fig. 9) and the vertical authorised flight corridor (represented by the red line on the top of the progress bar of altitude in Fig. 9)
- the horizontal alert limit (orange circle at the centre of Fig. 9) and the intervention limited surrounding the orange horizontal alert limit.

With this HMI, the operator is able to assess both vertical and horizontal trajectories with a single eye glance at the circles around the current horizontal position of the launcher. This current position has also been made more salient by using a larger green cross.

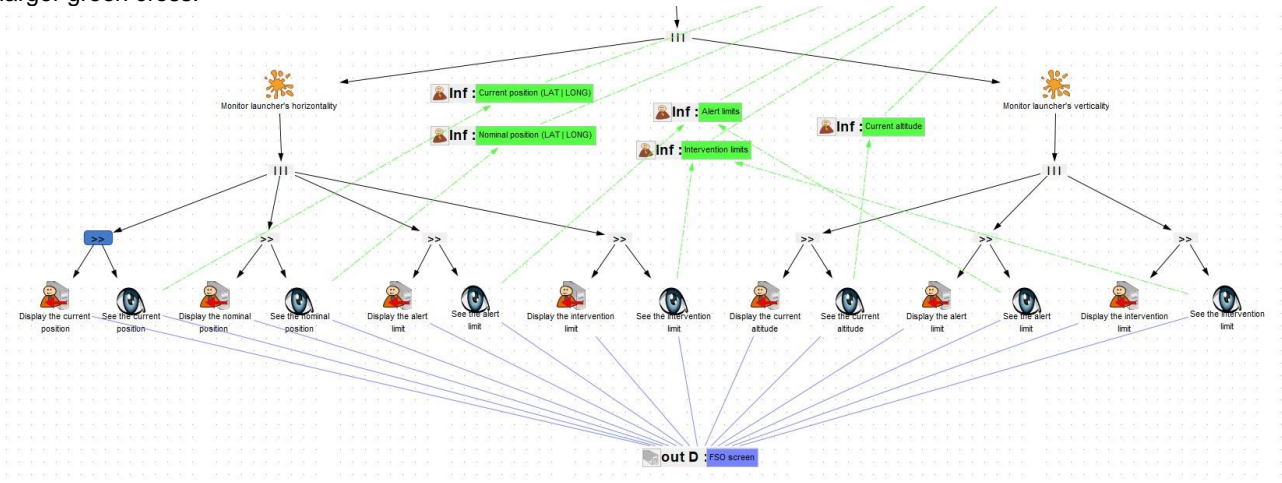


Fig. 10. Task model for the monitoring of the CALLISTO launcher for the third HMI presented in Fig. 9

The task models of the second and third HMI are the same (presented in Fig. 10). Indeed, the operator performs similar tasks using both systems and with the granularity of the task model, the models are identical. This contrasts with the task model of the first HMI presented in Fig. 6, which is far more complex due to the exploitation of dual displays. While being simpler, the task model presented in Fig. 10 represents all of the tasks the operator needs to perform in order to monitor launcher's trajectory. The disparity between both task models is thus due to the difference of information distribution rather than a true reduction of operators' tasks. While the usability (mainly efficiency and effectiveness) of the second and third HMI is very different, it is interesting to notice that the task models are the same. This is because usability improvement takes place at a very low level of operators' activity such as eye movement and information perception and analysis that is not captured in the current task models. To have this level of description would require embedding precise detailed information such as the distance from one information to another one. We are currently working on the refinement of these models to gather this additional information and to extend HAMSTERS to be able to model them explicitly.

5 CONCLUSION

CALLISTO is the first step towards operating reusable launchers from the CSG. In parallel, the CDO has been designed to be compatible with such reusable launchers / landing vehicles. For the CDO ground segment design, the concept of the future Flight Safety HMIs (as well as those for all operators) has been designed within a dedicated contract, resulting in dynamic interactive screens. These HMIs will be used as a basis for the ground segment development whilst also taking into account the results of this specific CALLISTO HMI study. The aim is to have transverse HMIs, capable of managing launchers with and without return parts, in order to facilitate cross-learning between launchers.

The case study has demonstrated that the process presented in Fig. 2 can be applied and tuned to the design of several HMIs for reusable launchers. We have also shown that tasks description and prototyping support the identification of information and action needs and to provide concrete description of requirements.

This work has also allowed the identification of research challenges which will be studied in future work.

6 ACKNOWLEDGEMENT

Maxime Grateau (in 2021) and Nathan Goy (in 2022) carried out internships in the flight safety department at CSG achieving the models displaying the dynamic behaviour of CALLISTO launcher during the course of nominal and deviated trajectories. The design process of CALLISTO's HMIs has greatly benefited from their work.

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