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Dynamic Workload Management for Multi-RPAS Pilots

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Abstract – *This document describes a key aspect of NtoM, a concept of operations (ConOps) currently under development, which focuses on the awareness, productivity and safety of Remotely Piloted Aircraft System (RPAS) pilots controlling several flights at once in non-segregated airspace. An explanation will be given of how the ConOps suggests capturing, representing, managing and predicting the workload of the pilots. To illustrate some of the features of the concept, it was necessary to define a representation of the workload associated to the tasks. A synthetic task environment that used the NtoM prototype was built and used to evaluate the requirements of time and attention of pseudo-pilots based on their performance while executing the tasks and task overlaps, determine the top threshold of workload allowed for a pilot and detect incompatibilities among tasks. These values served as a reference to design demanding test scenarios, which helped to reveal weaknesses and inspire improvements that were addressed in the following stage of development.*

***Keywords**: RPAS, UAV, CPDLC, Workload*

Nomenclature

ATC	Air Traffic Control
ConOps	Concept of Operations
GCS	Ground Control Station
LLP	Lost Link Procedure
LLT	Lost Link Timeout
LOA	Level of Automation
NPI	NtoM Pilot Interface
NtoM	ConOps to which this proposal belongs
RPA	Remotely Piloted Aircraft
RPAS	Remotely Piloted Aircraft System

I. Introduction

At a time when the use of remotely piloted aircraft (RPA) in non-segregated airspace is technologically possible and sufficiently safe, a huge growth in the use of these systems can be expected as the remaining issues like traffic management, security and legal responsibility are gradually solved. The benefits and flexibility of these aircraft open up the market to a wide range of commercial services that, similar to any other business concept, will need to be supported by sufficient profitability to ensure success. In this sense, one way to optimise resources allowed by remotely piloted aircraft systems (RPAS) is to have one pilot or aircrew controlling several flights at once. While it can seem a dangerous idea, the truth is that the high Level of Automation (LOA) of these aircraft makes it perfectly feasible [1], even considering single-piloted RPAS in the more challenging military environment [2], [3].

However, in aviation, where safety is a key pillar, being technologically feasible and productive is not enough to support a new introduction, especially if it could affect the safety and performance of the rest of the traffic or the work of the Air Traffic Controllers (ATC).

The NtoM concept of operations (ConOps) was conceived to mitigate the possible impact that this parallel piloting could cause. It is under development at the moment of writing this document, but the proposal of the ConOps can be found in [4]. Although NtoM could offer several benefits in other scenarios, it is expected to provide the greatest profit by managing highly automated RPAS in non-segregated airspace. Its full potential would unfold with the widespread use and full exploitation of the Controller-Pilot Data Link Communications (CPDLC), which, assuming a long-term implementation of the ConOps, is considered the main way of communication. The term multi-RPAS has been chosen instead of multi unmanned aerial vehicles (multi-UAV) because the latter is usually associated to a swarm of small drones with a total or very high level of autonomy, cooperating to accomplish a low-level flight (LLF) mission at the same time, in the same area. But NtoM aims to help pilots control heterogeneous aircraft models, performing different kinds of missions, not necessarily in the same airspace, and having asymmetrical needs of ground crew coordination. The present document focuses on one of its main pillars: the management of the workload of the pilots. The first part of the document explains how to build the workload model that will be used by the system. It begins with the measurement of the activity of the pilot, which will be transformed into a representation suitable for the needs of the Scheduler.

This block also describes how the model could be

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updated as the conditions change or the pilot gains experience. A second part explains those situations requiring the evaluation of the workload and therefore the use of the model. It also suggests which information could be considered for the workload forecast. The last part details some experiments carried out to build a workload representation required to illustrate the behaviour and potential of the concept and the useful insights that these provided.

II. Building the Workload Profile

Parallel piloting can be safe enough if correctly addressed, and considerable research has been done in this direction [5]-[7]. In fact, it could even improve safety. Evidence can be found on the decrease in awareness and attention when pilots have to deal with long periods of monotonous monitoring, which results in an increase in both reaction time and the number of lapses and errors [8]-[10]. A goal of NtoM will be to find a balance, overlapping periods of activity and periods of monitoring of different flights to avoid boredom but also dangerous situations of excessive workload. To have such a system that is able to balance, manage and predict the workload, two pieces of the NtoM system, the Workload Monitor and the Scheduler, need a representation of the resources required by the tasks and the thresholds and constraints to be considered. The following subsections suggest the steps needed to obtain the pilot's workload profile model required by these components.

II.1. Workload Measurement

The first step when building the model was to decide how to represent the workload. To provide NtoM with a high level of flexibility, its internal representation of the workload is abstracted from the way it was measured. In this way, each air carrier can use its own resources to determine the stress of the pilots. Fig. 1 illustrates this idea. The Workload Profiler will take the measurements as input to transform them into the representation that will be managed by the system. The closer to reality the situation measured, the better prediction and scheduling achieved. These measurements will reflect the Ground Control Station (GCS) usability, aircraft capabilities, mission and procedures, the LOA, and the pilot performance profile. Several studies have been conducted on the workload modelling of pilots, even for the specific topic of multiple UAVs [11]. These rely on measurements and modelling tools with different levels of sophistication, and try to provide clues for the system designers in the initial steps of system development or in the process of optimising any detected source of high workload or task parallelisation incompatibility. The analysis of the workload is usually assumed as a scheduling of resources, where these resources are the requirements of the attention and cognitive processing of the operators, or the sensory and psychomotor needs involved. An approach like this fits well with the need of NtoM to reflect different combinations of aircraft and GCS. The measurements of those tasks that are performed very similarly in a different scenario can be leveraged to reduce the number of new measurements, and such a similarity can be detected if the task is described as a set of resources. Measuring mental workload can be done by analytical (modelling) [12] or empirical approaches. The latter include a wide variety of methods: physiological measurements like electroencephalographic activity (EEG), functional magnetic resonance imaging (fMRI), near infra-red spectroscopy [13], positron emission tomography, eye movement, pupil dilation [14], or heart rate; behavioural measurements, which analyse the impact on performance when the level of workload varies; and subjective measurements(during experiment or post-experiment surveys, like the subjective workload-assessment technique or SWAT).Whatever the option, all pilots should be measured in the same way and the measurement must provide, for each task, the average time required by the pilot. When the evaluation is done by surveys, the workload level will have a single value, while biometrics will provide a variable value throughout the performance time. Surveys may seem cheaper, but to avoid interfering with the work of the pilot these should be performed during or after simulations. Measurements must be updated when conditions change which, requiring simulations, means taking the pilots away from their duty each time. If the evaluation of the surveys has not been automated (paper surveys), a data analyst will be required each time. Instead, biometrics can provide several advantages, especially those registered using wearable that do not hamper the pilot's activity, like belts or cuffs, or those using cameras. These could be integrated seamlessly into the usual activity of the pilot and the events to be captured measured as they appear.

Another interesting point of the physiological measurements is that they can reflect the impact of the accumulated time. This would allow the system to predict fatigue and reduce the cognitive load threshold.

II.2. Workload Profile Model

In the representation of workload chosen, each task or task overlap has a pair of values associated: the level of attention or dedication required and a time range during which the pilot is quite probably executing the actions involving that task. Building a personalised workload profile (instead of the same model for all pilots) provides a rich description of the relationship between task load and mental workload [15]; that means the possibility to detect those skills in which each pilot stands out (also those that should be trained more) or how these evolve as the pilot gains experience. The workload evaluation in NtoM has some points in common with the U.S. Army Research Laboratory modelling tool Improved Performance Research Integration Tool (IMPRINT) [16], based on Wickens' multiple resource theory [17]. This tool helps system designers to analyse the impact on performance and time duration for each task type when tasks are executed in parallel.

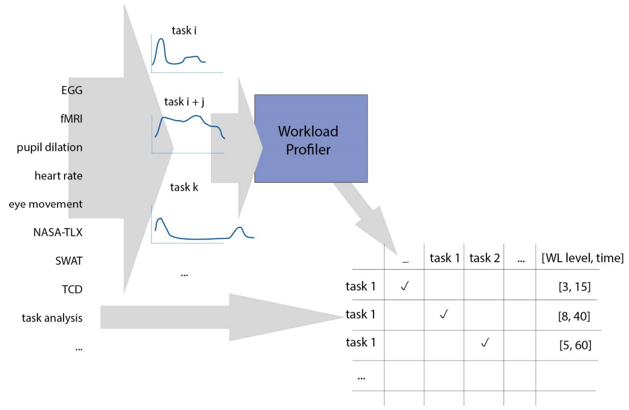

Fig. 1. Process of acquisition and initialisation of the pilot's workload profile. Measurements providing a variable workload throughout the task will be transformed by the Workload Profiler into a pair of values: a unique representative level of workload and the time required. It also estimates these values for the allowed task overlaps. Measurements providing a single value of workload directly populate the table

It provides not only information about the quantity of multiple tasks that a pilot can handle at a given time, but also about the incompatibilities among these tasks considering the resources (visual, auditory, cognitive, and psychomotor) required. It can also build the pilot's personalised workload profile. While the flight simulation is running, IMPRINT sums the need for each resource across tasks. By contrast, NtoM sums the workload of each task across flights. IMPRINT is oriented to the design of GCSs and procedures, while NtoM builds on top of these. As seen, in the model suggested, the value of the workload level of a task is constant along the period of time that the pilot usually needs for its execution; it tries to reflect the dedication required for that task. One reason for such simplification is that NtoM is procedural and GCS agnostic; it does not need to know exactly how the task is performed, just its duration and the possibility of parallelising more tasks (the workload level). This provides greater flexibility to the pilots. With a representation close to the input workload measurements, the Scheduler would assume that the actions of the task are always executed at the same moment, or in the same order, suggesting tighter scheduling, which would work against the pilot's acceptance. The reality is that those actions have some degree of freedom on the time they can be completed (the next subsection provides an example).That independence from the particularities of the GCS appears also in the fact that the system conceives the GCS as an independent piece that is plugged into the system, concretely, to the NtoM pilot interface (NPI). Pilots select one of the flights in the NPI to load it in the GCS. The role of the NPI is to facilitate the task of controlling concurrent flights and detecting errors (further details in [4]).

This role separation may recall the relationship between the Playbook-enhanced Variable Autonomy Control System (PVACS) and the Geneva Aerospace's Variable Autonomy Control System (VACS) [18]. Like PVACS, the NPI is a high-level tool for multi-UAV management; and VCAS GCS could be compared to the GCS plugged into the NPI, providing a library to execute control commands. In both cases, the integration becomes a symbiosis: the higher-level part needs the lower-level interface to send control commands for the aircraft and receive status information, but the lower-level part benefits from the automation and planning that the higher-level part provides. The task overlap incompatibilities will be determined by the Workload Profiler (an example is given in the next subsection) but could also include subjective or normative constraints, e.g. not allowing some kinds of overlap even when the total workload was under the threshold. The result would be a kind of multi-tasking conflict matrix, similar to the one in [11] at a GCS level to define the incompatibility of resource overlapping among parallel tasks.

II.3. Workload Profile Initialisation

As stated previously, the goal of the Workload Profiler will be to take the input workload measures and transform them into a representation reflecting the needs and interest of the system. That interest, which makes it different from other multi-piloting approaches usually focused on the optimisation of productivity, is that the NtoM scheduling prioritises safety from the very moment of the allocation of resources. It also pursues pilot acceptance by providing a representation that respects each pilot's workload management strategy. The following simplified example describes these concerns.

Consider a workload measurement using some objective method registering a different level of attention during the task execution (Fig. 2, top, curves). A task could be considered a process that begins with an initial fixed action and can be followed or not by more actions or waiting times until a final action ends the whole task.

Excluding the first one, the remaining actions can vary their starting moment to some extent, as seen later. An example of a task would be attending to an ATC clearance, with the first action being the evaluation and reply to the message and the second action the execution of the instruction. In the symbolic measurement of workload of the figure, each peak represents an action, with amplitude that depends on its time required and a height of crest reflecting the stress, cognitive load, attention or whatever was measured. In the example appears a task1 with a couple of actions. Suppose now that a second task arrives to another flight while the first action is being performed. Here, human nature tends to finish the first task and then follow with the new one (Fig. 2, strategy 1). In this way, pilots try to avoid pending issues that stress them. Add to this that the pilots are aware that moving to the second task in another flight requires loading into their mind the situation of that flight, which has a relatively high cognitive cost. During the experiments, participants were told that replying to the ATC had greater precedence than executing an instruction that was already accepted. The problem with strategy 1 is that it does not follow that rule and can easily lead to the expiry of the air system timeout (in CPDLC, this is the time to reply after which the message must be discarded, forcing the ATC to swap to voice to clarify the problem). Strategy 2 will be more desirable; it allows a reply on time despite its two flight swappings.

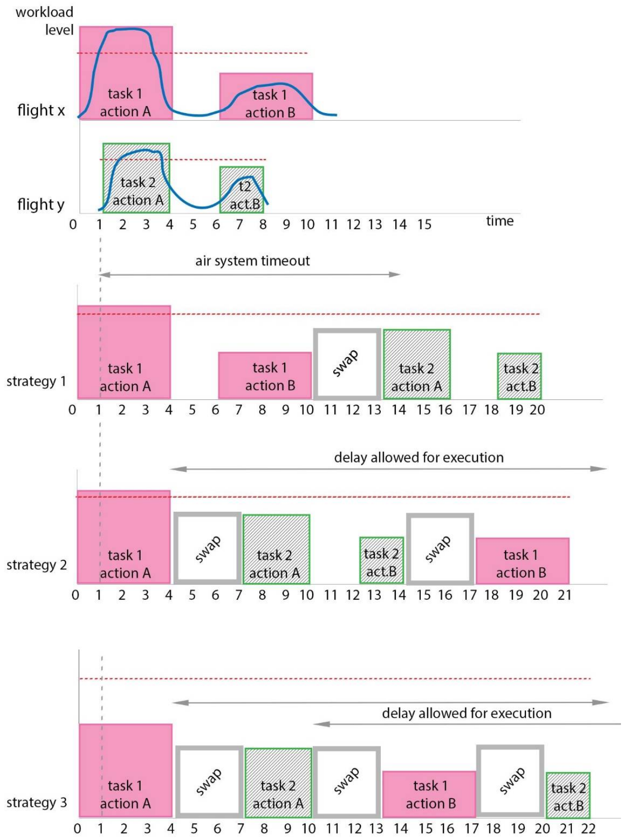

Fig. 2. Sequencing of actions in concurrent task execution

However, the Workload Profiler would not consider strategy 2 while allocating resources to deal with this situation; it would reflect a more conservative, worst-case option: strategy 3. The third strategy is the one that requires more time, because both tasks' actions are interleaved, which places a swap cost among them. It is also the option with a higher total workload (dotted horizontal lines) due to the fact that no more tasks could be overlapped to these because attending some other parallel action could let task 1 action B or task 2 action B out of their tolerable time to start the execution, which is another constraint to be considered to allow a task overlap. Allocating resources for a worst-case scenario covers any strategy selected by the pilot and provides some margin in case a problem or an unusual delay appears. Now, looking again at strategy 3, as has been said, it seems there is no room for a third task (consider another ATC request). But it could arrive at t17, just after the second action of the first task finishes, and the margin of time to reply provided by the air system timeout allows the pilot to finish action B of task 2 and then, released from any other tasks, attend to the incoming request. This means that the conflict matrix will have to reflect different kinds of overlapping for the same participant tasks, as not all of them imply an incompatibility. The number of these combinations could explode easily if we consider many different tasks and combinations, but it could be reduced by classifying the tasks by type according to their number of actions and cognitive effort, like in [19] for the manned case using the physiological data associated to the task. The implementation and test of the Workload Profiler using biometrics is the next step of development of the ConOps. It is expected to have greater flexibility than the previous example, for instance, including the characterisation of actions to constrain the strategies among which the worst case is selected, like immediate actions that could not be postponed on behalf of others, general precedences among actions or tasks, or tasks with a [*level*, *time*] value dependent on an input parameter or the aircraft readings. This work will also try to find an appropriate way to determine the workload threshold of a pilot.

II.4. Workload Profile Update

As the pilot gains experience, another component of the system, the Workload Learner, should check if that pilot's workload profile requires an update. How and when doing that update depends on the availability of the measurement. Pilots could periodically work using a wearable to record their physiological response (like a wireless EEG headset, a chest strap or a wrist-worn heart rate monitor); or the measurement could be done by non-invasive methods like cameras to track pupil dilation or thermal imaging [20]. If the system does not have access to such measures, it could try to infer the skill improvement. The case of the time required for execution would be quite straightforward if a remarkable decrease in the average of time required is maintained during a period. Detecting a decrease in the cognitive load does not seem so easy but it could be estimated based on the performance. In the NtoM system, the GCS Monitor registers all pilot actions, for instance to detect possible errors; that information could be used to analyse the evolution of the performance of the pilot overtime.

Whatever the method, the Workload Profiler would receive the new measurement to update its associated cell and propagate it to any other cell of task overlap were that value involved. This could also be done just to substitute the estimated value generated during the initialisation with real-life measurements for a given task overlap. Another function of the Workload Learner will be to determine the need to update the pilot's *red-line* of cognitive workload [21], [22]. This threshold, representing the amount of workload that a pilot can handle within an admissible decrease in his/her performance, may vary for each pilot (as illustrated by [23] for the ATC case); and it can grow as experience is gained. The fact that the Workload Profiler could decide that a task overlap is feasible given the independently measured costs per task, does not mean that the pilot will be able to deal with it correctly if the total workload level is over the pilot's capability of management. Subjectivity is reluctant to be expressed as a linear relationship and each pilot's limits could be determined by different contributions. Then, that *red-line* will act as an added constraint to allow a given overlap of tasks. The Workload Learner could update that threshold based on the evolution of the performance of the pilot (like a decrease in the number of errors or response time) when facing high demanding situations. The development of the Workload Learner is a future work that requires a well-advanced implementation of the system and a large set of experiments to capture the evolution of the skills.

II.5. Workload Monitoring

Like IMPRINT does, during the flight, NtoM keeps a constantly updated graph of workload forecast for the remaining trajectory. IMPRINT provides this feature to help the system designer to detect potential problems in the future system; NtoM will use it during the operations to detect and avoid unbearable levels of workload or task overlap incompatibilities. Those conflicts will be recognized by the Workload Monitor checking the task overlap availability in the aforementioned conflict matrix. When there is a task overlap incompatibility during the simulation, to IMPRINT this means an increase in the time estimated for the task being performed or the impossibility to perform the task. To NtoM, that would mean a hard constraint if detected during the pre-flight scheduling or, during the flight, a transfer of flights or some other contingency measure decided by the Event Manager, responsible for the management of contingencies. The continuous update of the forecast -in the prototype every 10 s -is necessary because any change of speed, or any deviation from the original flight plan will move the tasks from the moment they were expected during the pre-flight scheduling. The suggested representation and management of the workload holds the qualities of sensitivity (each task or task type has its own description), being continuous, predictive, context-rich and non-intrusive. The qualities of continuous, predictive and context-rich can also be found at a cockpit levelin an adaptive associate system when it comes to monitoring the state of the pilot, predicting his/her future state, and smoothly reacting to adjust the pilot's level of workload by providing automated support or re-allocating tasks [11], [24], [25].

In NtoM, the context-rich quality comes from the fact that the resource requirements of the tasks vary depending on whether other tasks are performed in parallel, to reflect the impact that sharing resources has on them [26]. The quality of continuous would be provided by the Workload Monitor. Besides its constant updating of the workload timeline, during the operations, whether relying on biometrics or analysing the performance, it would check that the pilot is assuming the workload within normal limits or would ask the Event Manager for a contingency measure otherwise. As a monitor and manager of the workload of the pilot, the idea behind this is similar to that of adaptive associate systems. While the adaptive system relieves the pilot by taking control of tasks, in NtoM the Event Manager would try to mitigate the overload or would apply a transfer of flight(s). The evaluation of strategies for such mitigation could open its own branch of research.

Considering that the transfer of flights should be a last resort, a solution could come from the coordination of the flights involved [7], for instance with a change of speed in part of them to avoid the coincidence of tasks, or assisting the pilot somehow to alleviate the usual workload level or time required.

III. Scheduling Needs

There are several situations where the Scheduler will use the workload forecast. Before the operations, when used as a workforce scheduler, the availability of the pilots is taken into account to suggest a combination of assignments to minimise human resources while keeping a safe level of workload for every pilot. Then, during the flight, several events could require finding a candidate pilot to receive a flight, and that pilot's current and future workload should be considered regarding eligibility. For instance, pilots can ask for a release of specific flight(s) if they consider that their current workload is too high or they are having any contingency that requires focusing on the affected aircraft. As mentioned in the previous subsection, reschedulings can also appear as a result of a request from the Workload Monitor, if it detects that the current load or the load at some point ahead overpasses a threshold, or if the current performance or measure of stress suggests some problem in handling tasks. NtoM also has a Supervisor role, who could force a flight transfer. The Scheduler would suggest to the Supervisor the best candidates available and the criteria they met, so that he/she can make an informed decision. Finally, the GCS Monitor keeps track of the pilot's actions. When these are disobeyed or forgotten, and the pilot does not correct or justify his/her actions after a warning, an automated rescheduling and transfer could be forced as the pilot's incapacitation or jamming could be assumed. To estimate when or where the tasks will be performed throughout the flight, the Scheduler can make use of different sources of information. Its main reference is the flight plan, with the tasks projected along the route. A second source, during the flight, would be the ATC instructions, which can add tasks, make the initial tasks vary or just disappear (an example of this appears in [27], Workload section, screencast 2). The system is able to recognise the tasks behind the instructions thanks to the use of CPDLC, which allows it to interpret unequivocally the semantics of the messages. Where CPDLC is not available, an option would be speech recognition [28]. A third source of information could be a *workload hotmap* built by the Workload Monitor. It would store the expected workload for each combination of waypoint, day of the year and hour. The map would be initialised using historic data with some relation with the stress, like the usual number of ATC communications in the area, traffic density or weather. The Scheduler would check this map to consider the possibility of an increase of tasks while overflying the area that, added to the scheduled ones, could generate an overload. As mentioned, the Workload Monitor constantly tracks the workload and response of the pilot and this information could be used to update the initialisations of the map, as each of the waypoint samples is overflown. The aggregation of the real experiences of the pilots would draw their perspective in the area, which could not be the same as that of manned aircraft pilots, especially if the final integration implies specific procedures, airways or conditions for the RPAs. Eventually, such a description could provide useful information for the air traffic management. Finally, the Scheduler could make use of online information like weather reports or incident notifications to reflect the increase of workload that such situations could add to the timeline. Another feature of the NtoM concept that could affect the assignment decisions are the preferences. These could be defined by the supervisor or someone in charge of the staff to specify which criteria should be followed by the Scheduler when having more than one pilot available once all the constraints have been applied. These preferences could be time related (priority to choose certain pilots in a time slot), skill related (pilots specialised in some tasks or those who need to practise them) or even related to the area overflown. No matter the criteria followed to define a preference, they define what has been called *stages* in NtoM, which can be understood as segments of the flight during which a preference for certain pilots applies (Fig. 3).

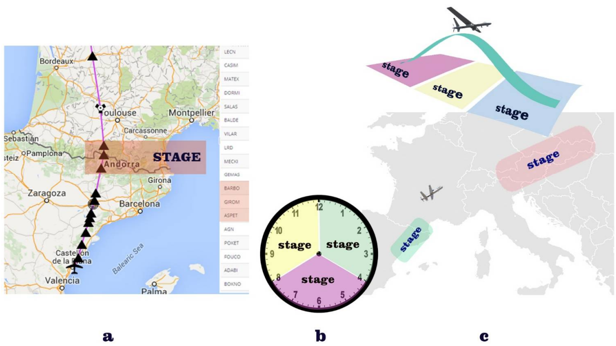

Fig. 3. NtoM Stages are pilot assignment preferences that can be delimited by temporary, geographic or flight stage criteria

Taking into consideration constraints and preferences, the Scheduler should try to minimise the number of required handovers, for instance avoiding an assignment to a pilot that is ending his/her workday. An appropriate balance of the total flights among pilots will contribute to this too. If a pilot is assigned with several flights, too close to the workload threshold, and some problem appears, it will be easily exceeded, probably requiring a transfer of flights. In addition, maintained in time, an excessive and unbalanced load could contribute to occupational burnout.

IV. Method

The workload management approach and tools proposed here are just part of NtoM. To illustrate the whole concept, test some of its features and discover its weaknesses, a prototype of the system orchestrating the ConOps was implemented. This first mock-up is far from containing the whole set of features that the concept suggests, and it was mainly focused on showing its potential (some screencasts can be found in [27]). That implementation and the examples of the behaviour of the system required performing the experiments described here, which correspond to the first set of tests. For instance, there was a need to design examples of tasks and determine their [*workload_level*, *time*] values somewhat. That way it could be shown how the system keeps an internal forecast of workload for each flight and how it is dynamically updated due to changes of speed or trajectory ([27], Workload section, screencast 1). The overloaded multi-RPAS scenarios of these experiments were designed to find out the workload top threshold, detect monitoring needs and inspire measures in the workload management and the usability of the pilot interface. Some of these findings were later implemented, put to test in a second set of experiments, and their results described in [4]. This section describes the environment, the sample tasks conceived, the test scenarios and how the workload was represented.

IV.1. The Environment

The synthetic task environment used the NtoM prototype with some modifications. For instance, to avoid having a person in the role of the controller, the ATC requests were automated. Following a script, which determines the moment, the kind of message and the parameters, the system sends the scheduled requests to the pilots. This allows the creation of specific demanding situations, like receiving several requests at once or very close to each other, and checking how pilots deal with it.

The prototype makes use of RAISE [29],a simulator environment developed by the ICARUS research group to evaluate the impact of RPAS integration in the Air Traffic Management (ATM). It extends Eurocontrol'se DEP simulator [30] including several UAV models and ADS-B-like (Automatic Dependent Surveillance-Broadcast) outputs with the aircraft readings. The NtoM prototype consists of a server and three different clients for controller, pilot and supervisor users. The clients and server communicate with each other using the RTI Connext connectivity framework [31], compliant with the Data Distribution Service (DDS) standard, which allows the simulation of different scenarios of Quality of Service (QoS) for the data communications. Considering that the participants could not have knowledge about piloting, the GCS that in a real implementation would be plugged to the NPI, was reduced to a minimalist panel of commands and placed in the same client, which also contains the CPDLC display [32]. The flight plans handed to the participants were printed intuitive diagrams depicting the tasks they had to perform when reaching some of the waypoints (Fig. 4, top). The diagram also shows the links and lost link procedures (LLP) projected during the planning of the flight. Participants were encouraged to mark the tasks as completed when done and write down any change in planned frequencies or LLPs during the flight (to organise themselves but also to communicate the changes during the control migration exercise). The tasks were artificially designed to represent different sets of actions and cognitive resources. The level of workload per task was established based on observation and the time required for each task was calculated as the average time executing the task among all participants (although, ideally, each pilot should have his/her own mean). (Fig. 4, bottom) shows an example of those values as seen by the Supervisor in the workload timeline.

IV.2. The Tasks

While the tasks do not try to reflect real-life procedures, but only different examples of mental workload for experimental purposes, they tried to represent the usual tasks required, as described by a subject matter expert and military RPAS pilot. Some more were practised by the participants (changes of altitude, speed, and handover) but the ones finally included in the measurements of this first set of experiments were the following:

a) *Change of Command, Control and Communications (C3) link.* Scheduled in the flight plan, and associated to the overflight of a waypoint. Participants do not have access to a map depicting the coverage of each frequency, but they can see the minimum quality between the past and next waypoint, and between the next and following waypoint (Fig. 5). For simplicity, the quality of the link was summarised as a value from 0 (no coverage) to 3.

For some of the scheduled link changes, they would find that the link quality was 0, which meant that the frequency was unexpectedly unavailable. Then, they had to evaluate another frequency or band. Ideally, if the diagram indicates changing the link when reaching a waypoint, they should update the link just after passing it. If they do it too late, the aircraft could exit the buffer area (an area where the previous and next frequencies coverage overlap, providing a margin of time to change the link), and they could lose the connection. In addition, the change should not be too soon to not exceed the Lost Link Timeout (LLT) value when there is no coverage for the new link in the segment left behind. The current LLT (the seconds in lost link before the aircraft starts to execute its LLP [10]) is shown in the flight strip. The participants would learn with practice that the evaluation of alternative links when the scheduled frequencies fails, requires time, so they would begin to check its availability before reaching the waypoint, to avoid exhausting the buffer area. This is why we find a *pre* and *post* time value in the time window for this task. The other two tasks are triggered by events, so they only have a *post* time associated. For the link, they could select directional antennas or satellite. With the first option they had seven frequencies and had to try to always keep the primary and secondary links alive and with the maximum quality possible, especially the primary link. The ground link was only lost if the primary and secondary links had 0 quality. By satellite, they had two bands to choose, without a secondary link. Before applying the change of link, after choosing an option in the dropdown, a preview showed the minimum quality of the link in the current and next segment if the selection was applied. Fig. 5 represents the link qualities in a similar way to the preview; the out of coverage icon for 5550 between RKN and SPY means that, while it could have decent quality in the rest of it, at some point in that segment the quality is 0 and hence 5550 should not be used in that segment.

Between HMM and RKN its minimum quality is 1; the real quality at every moment would be displayed by the GCS.

b) *ATC instruction to change the current LLP.* In an RPAS, the LLP loaded in the aircraft Flight Management System (FMS) will be executed if the link with the aircraft is lost and the LLT expires. By default, in the prototype, the LLP is automatically updated when necessary throughout the flight, according to the flight plan, but in the experiments, the controllers eventually asked the pilots to change it (supposing it consisted of landing in an area not available at that moment) to create a demanding situation. Participants were handed a printed chart, where they had to find and select an alternative plan depending on the current position, altitude, and fuel/battery level [10]. They were guaranteed that this alternative plan would always exist, so they could always reply WILCO to these messages. After the update of the plan, they had to send a free text message to the controller with the new plan selected, simply identified by its name in the exercise.

c) *Direct to clearance.* Assuming that previously the pilot asked for it, the participant receives this kind of clearance. Before answering, the pilot must check if there is a link available for the segment between the current position and the destination waypoint. If it exists, after sending a WILCO and applying the command, the participant must check if there is a need to change the current LLP in the shortcut. If it needs to be changed, the ATC must be notified with a free text message.

IV.3. Workload Measurement of Isolated Tasks

Subjective values based on the number and kind of actions required, and the complete dedication or attention observed, were used to weight the task load.

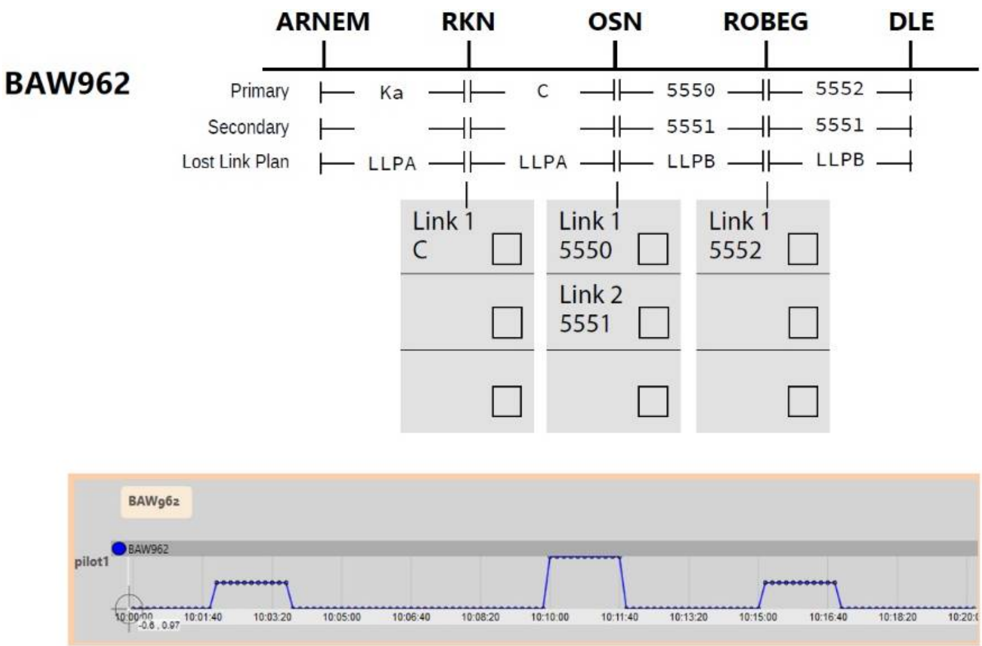

Fig. 4. Top: printed diagram of scheduled tasks for a flight handed to the participants. Bottom: workload timeline for the previous tasks

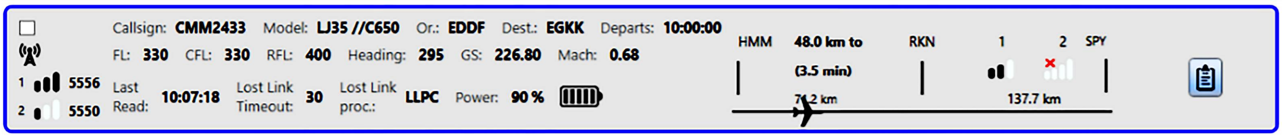

Fig. 5. Flight strip in the pilot interface showing the current link quality (left) and next segment quality if the current frequencies are maintained once past the next waypoint (right). The values represent the minimum quality along the segment or worst case

It should be noted that in a real implementation these values would be extracted from the workload model obtained from the measurements of the specific GCS and procedures. For example, in the present exercises, the change of the C3 link, which should not be delayed to avoid losing the aircraft, received a value of 3 out of 5. It could be argued that such an important task should receive a higher value. The reason is that the simple input element, with the preview that clearly shows the availability of the frequency, allows a quick decision and execution, in a matter of seconds. If the planned frequency has an unexpected quality of 0, the impact is suffered mainly in the time to perform the task because the pilot will check other frequencies to select the alternative with higher quality. An increase instress could appear if the task is started too close or passing the waypoint, the planned frequency is not available and the alternative has to be quickly found to avoid consuming the buffer area. But that would not be inherent in the task, and it is assumed that it is executed with its appropriate timing. This is an example of how the specific design of the GCS could influence the time and level of dedication required by the task. The LLP change was also weighted with a 3, which could be considered too high for a non-urgent task. The reason behind this is that, while using the alternative plans chart, the pilot moves all his/her attention to the booklet, which is a relatively slow action; after that, refocusing on the monitor and resuming a picture of the situation seems to require extra mental effort. The *direct to* clearance received a 4 because it contains demanding and pressing actions, particularly having to check the link availability and reply to the message before the air system timeout.

Tasks requiring complete and immediate dedication like contingencies, or the control migration, especially for the receiving pilot, would receive a 5. The default value for any flight, when it only requires an eventual monitoring, is 1, to reflect that the very fact of performing concurrent tasks, even when they do not consume any relevant resource at a given moment, adds extra workload; this is known as the *cost of concurrence* [33]. Again, it should be stressed that the tasks were deliberately ballasted. The printed LLP chart could be easily embedded in the interface and show the pilot the alternative plans considering the aircraft status; but the aim was to simulate a situation where the pilot is focused for a while on a specific task, making a decision, while keeping in mind a picture of the situation of the rest of flights and the time left to execute any next or pending action. The time amplitude of a task was measured as an uninterrupted period between the first and last interactions with the interface to execute that task. This representation of the tasks and task overlaps placed in a timeline with a time span that varies depending on the concurrent tasks, may recall those task interference models, which only evaluate the incompatibility depending on the time required for the concurrent tasks and the time available, like the Single Channel Theory [34]. However, these models consider all tasks as equally demanding and would avoid overlaps of long low-demand tasks, which could be perfectly overlapped. Weighting the tasks or their overlaps based on their cognitive load, the present approach becomes more similar to the Single Resource theory [35], which determines the difficulty of the tasks as the determiner to limit the parallelisation. Six participants of a range of ages between 18 and 60 years and advanced experience using computers were trained about the needs of the simulated RPAS, the CPDLC, and how to use the interface. First, they practised four scenarios containing the different tasks. After the training, each of them piloted from one to four scenarios with a single aircraft each, where the tasks appeared sufficiently separated so as not to influence each other. That served to measure the average time required to perform each task.

IV.4. The Multi-RPAS Scenarios

Besides the maximum total workload, other exclusion criteria are allowed to avoid undesirable situations if only the quantitative limit is considered. For instance, in the experiments there was a maximum of six flights per pilot, no more than one handover at once or a maximum of two concurrent link changes.

While the limit of workload was never exceeded during the pre-flight scheduling, it would be surpassed at some points during the exercise because of non-scheduled events: the ATC requests. No measures were applied in these situations by the system, as they are part of a future stage of development and the purpose here was to check the suitability of the threshold, identify the pilot's workload management strategies or any usability weakness or aid in these stressful situations. Four participants performed two scenarios, each one including four aircraft during the en route flight stage, with a duration of around 12 minutes each. The tasks, sometimes placed very close together or overlapping each other, were the following, distributed throughout the four flights:

- *Scenario 1:* Two changes of secondary frequency; one change of both primary and secondary frequencies; three more frequency changes with the planned link unavailable; three *direct to* clearances, just one of them feasible; and four LLP change requests.
- *Scenario 2:* Two changes of the secondary frequency; four frequency changes with the expected frequency unavailable; six *direct to* clearances, just three of them feasible; two LLP change requests.

V. Results

Following are the observations of the performance under the high level of workload recreated in the scenarios. Results are analysed in the Discussion section.

V.1. Time to Reply to ATC Messages

NtoM tries to avoid any delay in the response time that the multi-piloting could add to that implicit in the use of data link [36], [37]. While writing this article, no previous research was found on the delay in the RPA pilot communications using CPDLC, but [37] analysed the delay of unmanned aircraft and voice communications and this can serve as a reference to some extent. Among all the components of the end-to-end response time, NtoM could try to mitigate two of them. First, the equivalent to the *pilot verbal communication delay* [37], defined as "*The lag between the end of the ATCo clearance and the beginning of the pilot's read back*"; here, the term "verbal" should be removed or substituted by "data link", and the beginning of the read back would correspond to pressing the button to send the reply. The second component would be the *pilot execution delay*, defined as "*The lag between the end of the ATCo's command and when the pilot begins to initiate the manoeuvre*", which in this case would end when the pilot sends the command, excluding the time required for the command to reach the aircraft.

In the results, the response time to the request for an LLP change and to the *direct to* clearance were separated because the first one does not require an evaluation (was always WILCO), but the *direct to* required checking first if there was a link available for the shortcut. Table I shows the values of the *pilot data link communication delay* in three different situations: the message arrives while monitoring a single aircraft, while monitoring four, or while monitoring three and performing a task in a fourth. Only a couple of measurements could be registered for a case of having four aircraft and two overlapped tasks in different flights when the message arrives and the mean was 36.5 s.

TABLE I
TIME TO REPLY TO ATC MESSAGES IN SECONDS

1 flight	Mean (samples)	Median	Mode	σ
LLP change	40.9 (10)	37.5	73	29.82
Direct to	51.8 (5)	51	-	33.39
4 flights no current tasks				
LLP change	18.5 (8)	12.5	9	11.03
Direct to	15.82 (17)	14	8	9.79
4 flights one current tasks				
LLP change	22.33 (12)	11.5	5, 8	22.58
Direct to	22.63 (8)	13	-	17.72

V.2. Task Amplitudes

An excess of the *pilot execution delay* can also affect the air traffic management [37], which is why the Workload Profiler will reject any task overlap that could increase it beyond some limit. As with the delay in the ATC reply, this limit, which can be seen represented in Fig. 2, should be agreed and could depend on the final RPAS integration if RPAS are allowed some margin of tolerance with respect to manned aircraft considering the unavoidable latency.

Table II reflects the impact of the task overlaps in the task duration (which includes the *pilot execution delay*) and timing.

TABLE II
TASK AMPLITUDES IN SECONDS BY FLIGHTS AND OVERLAPPED TASKS

1 flight		Mean (samples)	Median	Mode	σ
LLP change		58.9 (10)	57.5	73	23.23
Direct to		99.8 (5)	103	-	51.66
C3 link change	pre	102.2 (18)	82.5	47	64.91
	post	5.57 (14)	4.5	2	5.36
4 flights					
C3 link change	pre	83.13 (8)	83.5	91	75.8
	post	2.5 (8)	1	0	3.25
2 C3 link changes	pre	41.08 (12)	38	67	29.90
	post	2.92 (12)	0	0	4.23
2 LLP changes & 1 C3 link change	LLP	82 (4)	76.5	-	50.8
	C3 pre	43.5 (2)	43.5	-	0.7
	C3 post	5.5 (2)	5.5	-	4.95

V.3. Errors, Omissions

Most errors had to do with the low experience of the participants with the interface and procedures, and these disappeared or decreased with practice. More interesting issues are those related to multi-piloting under stressful situations.

i. While doing the last action of a task, a participant receives a *direct to* clearance. He decides to finish the current task before sending the reply, contradicting the indications to this respect. While doing so another message arrives. He finishes the task, attends to this last message and completely forgets to reply to the previous one, getting a timeout. The top workload here was 12; the pre-flight scheduling threshold was 10.

ii. A pilot was executing an LLP change request when another one arrives for a different flight, to which he replies with a STANDBY before coming back to finish the previous task. This was unnecessary, as they were told that the answer would always be WILCO. He updates the first LLP but then realises that a link change is very close and starts to check the availability of the scheduled frequencies. He will forget to send the notification for the first LLP change to the controller, while the second message becomes a timeout. This stresses him so much that he fails with the link update because he was checking the link quality in the wrong segment; the aircraft exhausts the buffer area and loses the link. The maximum workload weight during this overlap was 17.

iii. With no other pending task, a user did not realise that one aircraft was reaching a waypoint where a change of link was planned, and loses the aircraft.

iv. A pilot receives an LLP change while there is no other ongoing task. He/she applies the change correctly, but forgets to communicate the new plan to the ATC. At this moment, a couple of aircraft were close to reaching waypoints with scheduled changes of frequency. In this same point of the scenario, another pilot replied WILCO to the instruction, but never applied the change of LLP. A third one even failed to reply to the message on time. The expected workload value when the instruction reaches them was 14, but it became 20 very soon, due to the pair of aircraft reaching the scheduled change of frequency. The reason why they left the LLP unfinished was probably because during the training, they were told to give preference to the more urgent tasks. In the end, an LLP is something that would be executed in case the link is lost; but if the frequency is not changed when required, probably the link will be lost (some changes of frequency were done just to improve the quality). So maybe they decided to attend to the other flights first and then just forgot to finish the LLP task.

v. In the previous situation, 70 s after the LLP change request and about 60 s before the two concurrent changes of frequency, a *direct to* clearance arrives generating a peak of workload of 18 units. Three of the pilots had previously lost that flight, so just one of them saw this message and was unable even to reply on time; he was too busy checking the availability of the frequencies and even forgot the STANDBY option. He failed to update the frequency of one of the aircraft.

VI. Discussion

The observation of the performance of the pilots during the experiments, even of such a short duration, made it possible to check live the statements of previous research about the engagement of the pilots or the strategies to handle the workload and confirmed the suitability of the suggestions for remote pilot stations found in [10] as a real need to improve performance and avoid errors. Even when managing several aircraft, when they could see that the closest task was some time ahead, you could see them bored, distracted, lost in thought, or looking at their smart phones. They usually reacted like this when the expected idle time ahead was around two minutes or greater. This sheds some light about the monotony of monitoring just one aircraft. Regarding the time to answer the controllers, it was between 15 and 51 s, depending on whether the message required previous evaluation of the answer and there were parallel tasks.

This is far from tolerable in a real scenario. In the manned case and voice communications, the average time, from when the controller starts talking until the pilot finishes the read-back was found to be about 11 s in [38]. [37] measured a mean of 2.5 s in unmanned aircraft simulations with a single flight, voice communications and no parallel tasks (contrary to the previous value, this does not include the read back). An added delay of 5 s is hardly accepted by the ATC [37]; then, the best case measured here, 15 s, would be somewhat accepted.

However, it should be considered that the present experiments were performed by non-professional pseudo-pilots with few opportunities to practise. In addition, the workload level reached many times would not be allowed by the system in practice. However, pilots' response and execution time visibly improved with practice, then a clear decrease in the response time could be expected in real conditions. In any case, some measures were implemented to help pilots to reduce this mark, like automated replies, reading aloud background messages or the possibility of replying using voice recognition.

Although it could not be inferred from the log, the observation of some of the participants showed that when the CPDLC air-system timer expired (100 s as per [39]) it was usually because the pilot forgot to answer the message, not because he/she was doing other tasks. It made clear that the visual icon notifying an open message was not enough the way it was, and it inspired a better way to highlight it. Only a couple of participants used the STANDBY message, which adds 100 s more to the timer.

One of the participants, when asked about what she thought of the fact that the response time was significantly shorter when she had several aircraft, said that she was quite a lot more engaged having the workload of the four flights scenario than with the boring exercises with just one aircraft, where the connections/disconnections of attention where sparser; with four flights she had to attend to the messages quickly to keep paying attention to the rest of the flights.

That, which corresponds to the Yerkes-Dodson law, should be considered the reason why the mean time amplitude of the task execution and the pilot communication delay decreases with several flights. It reflects the pilots' strategies to manage their resources to maintain the level of performance, something that has already been analysed for the specific multi-UAV case [40] and the ATC case [41].

Experience is related to the use of good strategies to manage the workload [42] and probably some task overlaps that led to errors could have been solved successfully with more training, or showing the pilots strategies to interleave the actions of parallel tasks to avoid timeouts and loss of link.

From the results, it seems that the intuitive maximum workload threshold of 10 during the scheduling of planned tasks was not misguided; errors begin to appear when the events raise the sum of workload weight to 12. In the following set of experiments, the threshold was lowered to 6 to avoid being easily overpassed when ATC instructions arrived.

However, in a final implementation, it would depend on each pilot's performance profile. Among the problems arising during the overwhelming overlappings, i) it showed the need to warn the pilot when the air system timeout (the time to reply to the message) was about to expire, and it was implemented. The iii) omission was addressed placing text reminders in the flight strip for close scheduled actions. To those instructions accepted but then partly or completely forgotten, the system would send a notification to the pilot showing the call sign and the pending action. These solutions can be seen in [27], Monitorings section, screencast 9.

VII. Conclusion

This document describes part of a concept of operations with the purpose of allowing safe multi-RPAS piloting in non-segregated airspace trying to avoid any impact on the work of the ATC. Specifically, it details the measures for the workload management. These features include a scheduler responsible for suggesting an assignment of the flights in a way that avoids the overlap of excessive workload. During the flight, the Workload Monitor keeps a constantly updated forecast of workload based on the readings of the aircraft and the pending tasks. It will also ask the Event Manager to apply some measure if a maximum threshold is suddenly exceeded or it will be in a point ahead of the flight. This measure could be, for instance, a transfer of some of the flights or a coordination of the flights to avoid the confluence of tasks. These components of the system supporting the ConOps will rely on a workload representation that transforms the input objective or subjective measurements of the pilot performing the different tasks in a couple of tables; one representing the task overlaps allowed, another to store their estimated execution time and the extent to being overlapped with other tasks (its workload level). Such transformation of the measurements will be the function of the Workload Profiler, the next step in the development of the ConOps.

To illustrate the features of the prototype and identify weaknesses and usability needs, a subjective description of the workload based on observation was used and some experiments performed. The scenarios simulated stressful situations to check when and why the pilots failed, and the impact on the time to reply to the ATC and execute the instructions. Those situations shed light on the level of maximum workload that should be allowed, but also on the incompatibilities among parallel tasks. At a usability level, checking what caused the errors inspired a set of measures to mitigate them, which were partially implemented in the next stage of development.

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