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Enhancement of the ESA mobile Procedure Viewer (mobiPV) beyond Low Earth Orbit

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Abstract

The ESA mobile procedure viewer (mobiPV) was initially designed to provide improved procedure navigation, visualisation and hands-busy interaction support for astronauts on-board the International Space Station. mobiPV also supported distributed team work through a series of collaboration services between on-board crew members and ground experts. Its underlying architecture, however, is not limited to operations on-board the ISS. This paper details some of the opportunities and challenges in providing operations support to explorers beyond LEO, whilst at the same time identifying additional mobiPV services that will be required in this novel context. Examples are given in the context of Cislunar and lunar surface operations, with emphasis on optimally distributed cognitive support for task execution. The discussion also includes a proposed communications infrastructure to enable enhanced mobiPV operational deployment. Spin-in technologies from the consumer market, including Internet-of-Things (IoT), as well as augmented and mixed reality are shown to fit well in the path towards a user friendly system, including teaching and coaching capabilities. Finally, the paper highlights how – in an iterative manner - early "beyond LEO" prototypes of the system can be demonstrated and evaluated – both as technology building blocks and as exploration operations support infrastructure – at terrestrial analogue environments such as the LUNA facility at the European Astronaut Centre (EAC), Cologne.
Keywords: crew information system, procedure viewer, collaboration, human exploration, cognitive support

Acronyms/Abbreviations

AR	Augmented Reality
CTH	Cislunar Transfer Habitat
IoT	Internet of Things
EAC	European Astronaut Centre
mobiPV	Mobile Procedure Viewer
NEEMO	NASA Extreme Environment Mission Operations
ODF	Operations Data File
VR	Virtual Reality

1. Introduction

The ESA mobile procedure viewer (mobiPV) improves overall task performance during complex manual activities for ISS flight operations. This is done by offering in real-time a workspace for the crew and ground teams to share.

Significant aspects of human space exploration operations beyond LEO for the crew information systems domain are longer mission durations, increased communication latency, limited availability and size of terrestrial mission control team, and more frequent local task sharing between (semi)intelligent agents and human explorers. Additionally, operations beyond LEO impact human performance in many ways; e.g. the complexity and hostility of the environment will be an order of magnitude higher than in International Space Station (ISS) operations.

The scenarios currently studied by space agencies also include a distributed exploration team; e.g. part of the crew in Cislunar and part on the lunar surface working together on mission objectives. This situation requires, among other things, a higher level of operational autonomy on the part of the explorers. Intelligent, mobile and worn-on task support devices can help achieve such autonomy.

The current ESA development "mobile procedure viewer" (mobiPV) is seen as a suitable platform to further develop into the required Explorer Operation Support System (EOSS). Nowadays mobiPV design for ISS operations is driven by the need to provide:

- a significant increase in situational awareness and involvement for the ground teams, combined with real operational interactivity with the on-board crew member;
- hands-free control – and wireless operations - of the interactive procedure viewer at any worksite inside ISS.

The goal is to increase overall activity performance and operational resilience for local manual systems and payload tasks. The collaboration features on mobiPV aim at smoothing out "bumps" during the execution sessions and/or avoiding re-scheduling an on-going activity because of real-time issues. All collaboration services afforded by mobiPV complement standard ISS Mission Control Centre (MCC) services, rather than replace them.

2. mobiPV in support of LEO operations

The mobiPV implementation currently deployed on the ISS supports stand-alone crew operations, as well as crew-ground collaboration. This development originates in the crew procedure viewer domain and it provides a space-ground shared workspace for procedure execution to increase overall awareness of activity progress. The mobiPV ground segment includes one, or many, geographically separated mobiPV Ground Terminal(s) featuring a functional identical set of services as the on board mobiPV device(s). mobiPV is able to parse and display standard ISS crew procedures, but the design of the system can be easily extended to include other standards. Such flexibility has already been successfully verified in one of the analogue NEEMO (NASA Extreme Environment Mission Operations) campaigns.

2.1 Task support

With a classical procedure viewer as a starting point – where a green step marker indicates the current instruction being executed – mobiPV offers the following additional services:

1. procedure voice navigation (e.g. to ease the execution of hands-busy activities);
2. any procedure instruction can be annotated with single or multiple text, audio, image or video notes, prior to, or during, procedure execution;
3. easy addition of one or more Assistive Displays – usually a tablet device – providing a larger screen real estate;
4. establishment of a collaboration session among mobiPV units enabling green step synchronization, and note sharing;
5. multimedia messaging;
6. audio conferencing;
7. video conferencing with up to two streams per mobiPV unit;
8. a session logbook, including notes and messages exchanged, built in real time on each mobiPV unit.

Items 1. through 3. also add value when mobiPV is used stand-alone. The Assistive Display (item 3.) provides an alternative interaction device, and offers improved operational context by displaying more instructions before and after the current one. Today procedure voice navigation only covers basic commands (e.g. next step, previous step, etc.). All photo and video notes are captured with the head mounted camera. The latter can also be used to follow astronaut activities in real-time through an astronaut eye view. Video from ground can be used to highlight to the astronaut areas of interest on an engineering- or science reference model. Merely showing a happy and engaged ground expert can also be very valuable for the on-board astronaut! The session logbook can be used to easily follow the procedure execution as performed during post activity evaluation, and for giving quick access to all exchanged media notes and messages. A more complete overview is found in [1].

Figure 1: ESA astronaut Matthias Maurer using mobiPV during NEEMO21. Credit: NASA.

2.2 Design and implementation

mobiPV consists of commercial off-the-shelf mobile devices and laptops. The custom software is developed by ESA and it is functionally identical between the on-board and ground versions of mobiPV. The current operating environments are Android and Ubuntu respectively. An explicit design goal is to keep the software as much as possible device and operating system independent. As new smartphones, tablets and related peripherals enter the market, the effort to transfer mobiPV over to new devices should be minimized. Such design philosophy is applied also to the media types used to complement text based procedures.

The required network infrastructure is IP based and relies on both TCP and UDP services. No commercial server outside the ISS domain is required for any of the services mentioned above.

The software code is available to interested parties under the ESA Software Community license.

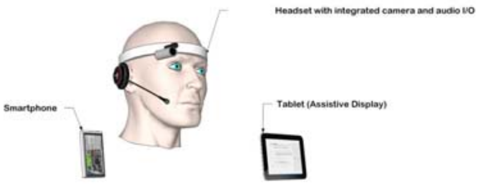

Figure 2: Current flight segment hardware

2.2.1 Flight segment

The mobiPV hardware on-board ISS today includes a Nexus 5 (Android). The user can optionally use any device with an up-to-date web-browser as an Assistive Display. The smartphone is connected to headset and head mounted camera by standard USB and audio cables. The smartphone's transmitters were removed during the space certification process to alleviate worries about electromagnetic interference.

A fully charged smartphone battery can theoretically support a mobiPV session of up to 5 hours. A shorter battery life is, of course, to be expected, if the head mounted camera is utilised frequently during the activity.

2.2.2 Ground segment

The mobiPV architecture supports multiple ground units. The default operations scenario for ISS is that at least three laptops participate in any given session with the on-board mobiPV unit: one is at the responsible mobiPV centre (EAC), one at the activity owner centre (e.g. a USOC), and finally one at the Flight Director console in Columbus Control Centre. Optionally, an additional node can be added to allow the mobiPV developer to provide real-time engineering support.

2.2.3 Communications infrastructure

The conduit for the required network services on-board is the ISS Joint Station LAN (JSL). mobiPV connects wirelessly to the JSL to access the on-board crew procedure library and to establish collaboration sessions with mobiPV ground units. When mobiPV supports an ESA sponsored activity, the Multi-Purpose Computer and Communication (MPCC) space to ground link services over NASA Ku internet protocol service (Ku IPS) is utilised.

2.3 Upcoming ISS features

A number of service, content and technology enhancements are planned to be added to the system currently deployed on the ISS.

2.3.1 Operations support service improvements

On the flight side, the smartphone user interface will soon be aligned with standard Android and iOS styles allowing for a more familiar and efficient user experience.

Integration with the on-board timeline viewer (OPTIMIS) – allowing the crew to select a procedure by simply clicking on the corresponding activity in the schedule – is currently considered as a way to make mobiPV a seamless component of the Station IT infrastructure.

Integration of multiple on-board nodes – i.e. multiple astronauts performing in parallel different activities with the support of mobiPV – is also under consideration.

2.3.2 Content trends

mobiPV currently supports the standard ISS crew procedures, also known as Operations Data Files (ODF), with their in-line images and external reference documentation. The format of such procedures is based largely on legacy paper formatting conventions and it is no longer adequate in a context when all procedure are consulted in electronic format.

A number of improvements are in-work in this area:

- inclusion of "how-to" videos as a way to replace traditional procedures;
- integration of VR content into the Reference Document repository of the procedure library, leveraging the work already performed by ESA in the field of Virtual Reality (VR) for on-board training.

Personalized procedure presentation is also slowly making its way to real-time application. As an example, a procedure author can currently decide to group together and collapse a set of detailed steps in an activity flow. At execution time, the crew can choose to keep the detailed instruction collapsed and work from experience, or have all the instructions displayed by the viewer. Additional mechanisms for tailoring procedure presentation at run time are expected in the immediate future.

2.3.3 mobiPV technology improvements

The list of planned technology improvements for mobiPV includes features that will be valuable for operations beyond LEO, such as

- basic augmented reality (AR) support;
- wireless head mounted camera and display;
- mobiPV ground router to minimize traffic on the space/ground data link.

Augmented Reality, for example, has the potential to enhance operations also when remote guidance is provided to the crew. An initial step could be to overlay AR markers and labels, plus rendering of short crew instructions on relevant hardware.

Ease of hardware donning and doffing recurrently came up as a top recommendation during the various user evaluations. A wireless head mounted device, including camera, display, microphone and headphone is the solution under investigation. The head mounted display could show a simple replica of the smartphone (partial) screen or afford a more advanced visualization experience involving Augmented Reality objects.

2.4 Operations validation

Iterative development has been the baseline approach behind all mobiPV efforts to date.

Various versions of the system have been tested on ground by astronauts and flight controllers during several user evaluations of increasing complexity and operational fidelity. Tests included the handling of Training Models of ISS payloads and systems at the European Astronaut Centre, as well as more complex scenarios during beyond-LEO simulations. Specifically, mobiPV was evaluated in the underwater Aquarius habitat during NEEMO 19, 20 and 21.

Figure 3: ESA astronaut Andreas Mogensen using mobiPV in the Columbus module. Credit: ESA

mobiPV has also been tested in space during the iriss mission in September 2015. In this context, ESA astronaut Andreas Mogensen verified the end-to-end network connectivity with the ground, while executing standard procedure navigation and annotation tasks.

The next step is the execution of an installation and check-out as well as complete system assessment of an updated software version during inc. 53/54. Those activities will include the execution of an ESA payload activity with the support of mobiPV. This additional evaluation will trigger further improvements and software updates that will be eventually implemented and verified in the first half of 2018. The final intent is to make mobiPV a standard component of the ISS operations support tools.

3. Use of mobiPV beyond LEO

The agenda of the space agencies for human space flight operations beyond LEO proposes successively more ambitious operations scenarios including allowing crew greater autonomy and hands free abilities which have been found essential to planetary operations.

The nature and operations of missions beyond LEO is significantly different from LEO. In the context of mobiPV, those elements in particular need to be taken account of:

- exploration teams are likely to operate in lunar/planetary orbiting stations as well as on the surface concurrently;
- possibly weaker ground expert support, for cost and data link reasons;
- longer duration missions, with return time for humans to Earth in case of severe problems significantly higher than from ISS;
- during a mission payloads and systems are likely to gradually deviate from their as-built configuration.

Operations support content-wise is also likely to evolve compared to today's ISS tools, products and processes. The instruction driven procedure system deployed on ISS will change into mixed media operations manuals supporting the explorer to achieve a particular task. Provision of detailed instructions can still occur, on an as-needed basis.

In LEO operations, the mobiPV collaboration services based on real-time (video conferencing) and file transfer (procedure synchronization and note exchange) are all equally useful. With increased data link latency only near real-time services (media messaging) and file transfers (notes exchange) are operationally meaningful.

In general, mobiPV will become more useful if a partnership is established early on in the mission preparation and training phase between the a user and his/her operations support system. This capability, based on the discussion in [2], requires mobiPV to build and host a dynamic model of its user. The user model will be constantly adapted, and can always be interrogated and updated by the user him/her-self. The open architecture of mobiPV makes it suitable as the foundation for adding the partner capability required to evolve the system towards an intelligent operator's assistant.

3.1 Cislunar

In the Cislunar Transfer Habitat (CTH) the typical day-to-day on-board system and payload maintenance is expected to be similar as the ISS one. As of today, a distributed team of ground experts, some of them operating from small home bases, can be easily tied into a mobiPV ground network. Such a multi-node ground mobiPV support set-up would be beneficial to maintain situational awareness for all stakeholders on ground, which would improve collaboration, streamline operations, and quickly resolve issues.

A new mobiPV function could be the capability to adapt task instructions in real time to events and issues occurring during execution; e.g. the system could inject into an existing procedure appropriate Fault Detection, Isolation, and Recovery (FDIR) instructions. The required procedure will be invoked (if not already active) and the user will thereby be in a position to immediately address the contingency.

mobiPV could also support direct command and monitoring of small infrastructure and simple payload items through a direct interface. That capability will also provide an alternate download path to be used for non-foreseen contingencies, mainly by utilising emerging internet-of-things (IoT) technologies to sense and control, CTH experiments and infrastructure.

3.2 Lunar surface operations

The exploration team members will often be distributed over many locations; for example in a habitat on the lunar surface, in an EVA on the surface, or in a Cislunar transfer habitat. Support from mission controllers and ground based experts would also, most of the time, be part of the real-time operations scenario. Multiple mobiPV sessions will be required to support all parallel tasks in progress.

For the users in suit- or rover-based EVAs an additional interaction mode will improve performance for certain tasks; spoken instructions (Text-To-Speech synthesis; TTS) .

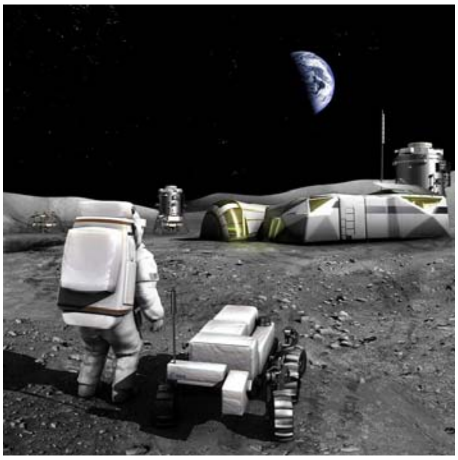

Figure 4: Lunar surface operations. Credit: ESA

In this new operational context autonomous operations will be prevailing and an intelligent explorer information system is required. A path to achieve this is to let mobiPV host a dynamic user model so a partnership between the explorer and his/her operations support system is established. For example, during terrestrial training and simulation activities the building of a personal user model can already be initiated. The user model will then be able to adapt operations and cognitive support provided to the explorer during actual mission execution based on previous experience. It is foreseen that a form of machine learning that requires a minimal learning set will be the enabling technology for this capability.

3.3 Beyond lunar operations

The Mars exploration environment will feature an increased number of (semi)intelligent agents operating with the explorers. To mediate between all goals and resource demands in that complex operational setting and still keep the human comfortable in his/her supervisory role, there is a need for a network of intelligent crew information systems.

The foundation for an intelligent operator's assistant is constant learning and knowledge retention (and adaptation) by the system. The system will learn by user actions and their outcome, processing media flows, and/or by direct input from the user. Reversely the system will coach the user based on current situation (goal and environment), and the dynamic user model.

The partnership put to use during lunar surface operations will, in this scenario, also include autonomous agents engaged in the same task as the human, or active in the same physical space. This fact will necessitate some level of dynamic modelling of its environment (equipment, agents and resources) in the operator's assistant.

3.4 Design and implementation goals

The main challenge for a crew information system is of course the fast evolution of technology and interaction styles. By having selected a modular networked architecture, C as the programming language and standard network services for the core system, future hardware upgrade and maintenance issues are minimized. As human computer interaction styles and devices change, e.g. web interaction versus mobile app GUIs, parts of the system will certainly be subject of sustaining engineering.

Extension of the dynamic user model must be as simple and non-intrusive as possible. Written (text notes and messages) and spoken words (mobiPV commands, audio and video notes) should be the default input methods. Subsequently, the system will process the information to build and maintain a user model. An editable human readable format of the model will also be available. Same situation holds for the required modelling and simulation of the environment, based on phase C/D design, as built-knowledge, and results from subsequent test campaigns.

3.4.1 User experience

Based on the development of a personalized user model, the interactions with the user can be tailored to the user needs and contribute to an overall better user experience.

For example, the user model will keep track of the training and operations performed by the user and use that information to estimate what the user may already know and what may, likely, have been forgotten. Using this information, the interface can be automatically adapted to provide very detailed instructions for unknown or untrained tasks or just a general high level flow for well-known activities.

It is also expected to extend the user model with instantaneous information derived from indirect monitoring of the crew. That information may help the system to determine the cognitive load of the crew and/or make suggestions on how to proceed, either adjusting the language, proposing to defer tasks to another member of the exploration team, or simply re-scheduling the task, if possible.

It is also expected that new interaction paradigms (and devices) will emerge in the coming years and those new ways to interact with the system will be progressively adopted for each of the beyond LEO operations phases. However, as it is difficult to foresee how user interfaces will look and feel in the coming years, it is better to follow a more general approach based on a richer user model.

3.4.2 Hardware and software

Hardware and software are expected to evolve and mobiPV will continue to be as agnostic as possible with regards to these two concepts. The distributed architecture of the system ensures its scalability even in the case the hardware development pace increases in the near future. In addition, special purpose computational devices, e.g. emerging artificial intelligence processors can easily be incorporated into the system, should they benefit the overall functionality.

However, these new exploration scenarios will bring new challenges, especially hardware-wise. Cislunar and lunar surface operations will impose further constraints on the hardware regarding radiation hardening, temperature ranges and light conditions during EVAs.

Use of mobiPV with a spacesuit will require important changes to the HW. The concept of a wrist-mounted device still sounds interesting however the touch screen interface will either need to be redesigned for glove use or a replacement found. A suitable alternative envisioned is a more sophisticated voice commanded interface.

3.4.3 Content aspects

The mobiPV system is conceived as a modular application intended to offer different services. From the procedure execution point of view, the following content is expected to be integrated in the near future:

- 3D animations. A three dimensional (3D) animation can be seen, in the context of procedure execution, as a interactive video in which the camera can be changed by the user to select the better point of view at any time;
- Augmented Reality (AR). This is the natural evolution of the 3D animations. Once the 3D animations are ready they can be used on an AR application with little effort. It will be especially valuable for on-the-job training sessions;
- emerging procedures style. The procedure will not be a static sequence of steps and instructions any more but it will become a live document enabling the user to command systems and adapting itself according to the responses from those systems. This will require the definition and development of new procedure standards.

These types of content are currently under research and some promising results have already been secured. However, there is still work to be done, especially in the authoring field to provide tools to easily create, and maintain, this kind of content.

Additionally, mobiPV can be extended with extra modules to enable the access to content from different domains. Some examples are:

- Inventory Management Systems (IMS). Closely related to the procedure execution, this is usually managed by a separate system characterized by high ground interaction. In an exploration scenario with limited ground support, the use of Near Field Communication (NFC) technologies to keep track of items, tools and supplies, will be required;
- specific system and payload displays. Nowadays, many system and payload interactions are performed from ground. This will be more difficult and, in some cases, impossible in a Mars mission. In that context, the use of graphical/synoptic displays will help to reduce the complexity of human-machine interaction. In the case of systems, it is expected that most interactions are accompanied by a procedure but for some instruments or tools a freer interaction may be required and the use of simplified interfaces will be very beneficial.

3.4.4 Artificial intelligence

Artificial Intelligence (AI) is one of the key elements for crew information systems during future exploration missions. The systems in those scenarios have to be smarter to compensate for the limited support from ground. It is indeed the human explorer that will have to solve the problem, with the help of powerful support tools.

As a first step, the use of AI to generate tailored procedures for specific situations is being considered. In this context, AI will be able to tailor procedures in situations like the following:

- a missing or broken tool: the AI can modify the list of tools included in a procedure to propose an alternative tool;
- same scenario but for a system component (e.g. an electronic part with specific voltage requirements): the AI can propose alternative components and also suggest how to adapt the voltage appropriately;
- previous repairs, and wear & tear, modified some of the exploration platform or habitat systems in a way that impacts the as-designed database: an AI could generate a new procedure to deal with the modified configuration.

In the medium-term, the AI will be present from the beginning of the mission and, ideally, will be learning together with the crew. This learning process may include, for instance, troubleshooting scenarios experienced by a previous crew but never seen by the new replacement team of explorers. In the same philosophy, the AI will know the as-design and as-built configurations of the different systems but it will also know the as-modified configuration described in the use cases above.

3.4.5. Infrastructure / network

In order to achieve some of the goals discussed above, the overall infrastructure supporting the exploration mission needs to designed for that. The use of the Internet of Things (IoT) technologies is envisioned in the future mobiPV. The infrastructure devices and systems can be network connected and able to report its state and also be configured/commanded through the network.

The immediate advantage of this approach is a performance increase derived from the fact that the devices can be accessed wirelessly. Compare this to many payloads today that requires a serial or USB connection with a laptop to be operated.

Furthermore, devices can become smarter and they can even contain their own manuals and procedures or even better a description of themselves that can be used by the AI described prior to the generation of tailored procedures based on the current situation.

A great advantage of this is that the explorer does not have to look for the procedure in a huge procedure library. A short list including only the list of procedures related to that device is immediately exposed to the user when needed, saving time.

Additionally, these procedures can already be customised to specifically interact with that device, including the right commands expected by it and opening the door to the automation of simple or routine processes.

4. Development path

Many avenues are available for the iterative development and evaluation phases required to successively reach the system described above.

Building block investigation, taking a slice of a use case and demonstrate a particular technology is a good way to proceed. Both for the stakeholders – including industry - to learn, but also adapt system requirement.

The planned LUNA lunar surface analogue facility at EAC could be used as a test deployment platform for the mobiPV system; both for building blocks and the integrated system. The LUNA facility is a ‘Mission-Focused-Analogue’, i.e. for highly integrated simulations with robots and humans in cooperative work and will be a platform for human focused exploration technology demonstration and testing.

The outcome of LUNA simulations will determine what can be put to use in terrestrial analogue missions for further consideration for on orbit demonstrations. Naturally mature capabilities foreseen for Lunar surface operations should be “field tested” already in the Cislunar setting.

Figure 5: Human – autonomous agent cooperation. Credit: ESA

5. Summary and conclusion

mobiPV as a support for human exploration beyond LEO is a low-cost enabler for distributed (spatially and timewise) collaboration. The various collaboration services are tailored to the operations context at hand. Individual and team cognitive support will also be offered by the system, due to longer duration missions and less mission control support compared to LEO human spaceflight operations. There is also a need for knowledge hosting & evolution at the source in an exploration mission, to which mobiPV will be a suitable crew interaction surface. Infrastructure required are always-on IP networks, and dynamic knowledge repositories. A mobiPV evolution of already available services, and adding an intelligent operator's assistant capabilities, will meet the needs of a team of explorers in operations beyond LEO.

Implementation wise spin-ins from the commercial market will continue to guide the evolution of the system, with open design solutions so supplier independence of software, network and devices can continue to be maintained.

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