# Wearable crew support technology on the International Space Station: the mobile Procedure Viewer (mobiPV)

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**Abstract**

Astronauts on the International Space Station (ISS) constantly rely on procedures for system and payload operations. These procedures based on the Operations Data File (ODF) standard have been traditionally visualized using print media and fixed laptops. Typical crew tasks on the ISS demand mobility and there is an increasing need for wearable, hands-free technologies that support procedure visualization and execution, simultaneously enabling collaboration with flight control teams on Earth. The European Space Agency (ESA) has identified this technology gap and is developing the Mobile Procedure Viewer or mobiPV. A user-centred crew support tool that relies on mobile computing hardware; mobiPV enables procedure execution, 3D data visualization in augmented reality, note-taking and provides peer-to-peer multimedia communications for collaboration, including text, audio and video communication and white-boarding. These features are provided in a mobile and hands-free manner relying on wearable displays and speech recognition technologies for user interaction. We walked through system concepts and initial UI mockups with end-users at the European Astronaut Center (EAC) and gathered their feedback on the system's features and expected usability. This article presents the state of the art in wearable systems in space operations, introduces the mobiPV system and discusses the main findings of the usability workshop.

**Background**

Human spaceflight and the International Space Station (ISS) program are enormous endeavours where governments, space agencies, industry and academia across many nations work together to ensure that the environment of space can be understood for the benefit of mankind. International crew-members live on-board the ISS for varying periods of time performing complex tasks ranging from assembly, inspection, maintenance, system operations and scientific investigations. ISS tasks can range from laptop usage procedures, robotic teleoperation, biology experiments to ultrasound diagnosis (non-exhaustive) and are at times time-critical, such as diagnosing a malfunctioning payload or performing an emergency routine. Although the crew are trained for most of these tasks on-ground, they are still required to execute these tasks following strict procedures on-board which are based on

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standard task description schemas such as the Operations Data File (ODF) (NASA, 2010).

**1.101 KUBIK 6 SETUP**
(KUBIK/ALL/FIN/HC) Page 7 of 8 pages

4.2 Align Centrifuge Insert (KUB-FM1-CI) on top of Kubik 6 (cut corner of the base plate, on upper left position relative to the front panel, Figure 9)

4.3 Insert Centrifuge Insert (KUB-FM1-CI) into Kubik 6

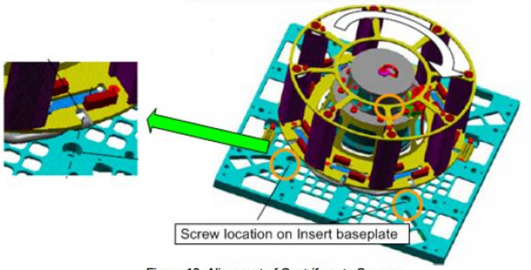


**Figure 10. Alignment of Centrifuge to Screws**

4.4 Align the holes on the Centrifuge towards the screws on the baseplate of the Insert (Figure 10)

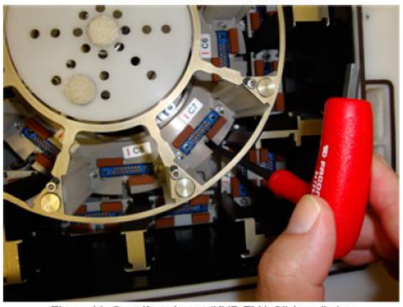

**Figure 11. Centrifuge Insert (KUB-FM1-CI) Installation**

*Figure 1. Payload ODF procedure with reference images (Courtesy: European Space Agency)*

**1.403 HIGH DEFINITION VIDEO CAMERA ASSEMBLY (HD-VCA) INSTALLATION AS VCA1**
(MSM/INC34/FIN/HC) Page 9 of 9 pages

3.3 Fix Fibreoptics Converter, part of HD-VCA SUP Cable, to SUP handrail. Use velcro ties as required (Refer to figure 10).

| CAUTION |
|---|
| Over-bending of HD-VCA SUP Cable may result in damage of fibreoptics. When coiling the minimum bend radius is 50mm. |

3.4 HD-VCA SUP Cable P08 →|← SUP1 J08 DATA5
HD-VCA SUP Cable P06 →|← SUP1 J06 DATA3

Carefully coil remaining cable length of Fiberoptics Cable and fix as required, using velcro ties.
Avoid Bending Radius < 50mm

4. CLOSEOUT

4.1 Take picture of installed HD-VCA and cable routing (Digital Camera).

4.2 VCA1 lens connector ←|→ VCA1 body

*Figure 2. Payload ODF procedure with warnings and symbols (Courtesy: European Space Agency)*

The ODF standard is implemented for almost all ISS crew procedures including subsystem, science, crew-health and payload operations. The standard is implemented for ground operations as well and used by flight controllers, payload instructors and operators. Figure 1 and 2 provide examples of system ODFs.

It might surprise some readers who expect that the astronauts working in microgravity execute these complex tasks aided by advanced displays and wearable computers that the crew still rely on print media and fixed laptops to view procedures (Figure 3).

These choices are not because space agencies want to keep their crew from using the latest, cutting-edge computers. Safety regulations and tough hardware qualification tests for space flight can at times prevent or significantly delay new technology from reaching the ISS. Today, dedicated software on these laptops provides access and renders the procedures which are uploaded to a flight database ahead of a crew member's activity.

On-board tasks are rarely performed alone by the crew. Flight controllers in Europe and the United States oversee and support the crew on a 24/7 basis. There are limitations here as well. Planning information and digital content needed is prepared in advance of the actual tasks because communication coverage, data approval and verification processes and available technical infrastructure impedes and delays the availability of real-time support from the ground. The only real-time channels are full-duplex voice and unidirectional video downlink. Even these are constrained to specific mission control centers, preventing other end-users, such as scientists or payload specialists from working directly with the crew. In the technical environment of the ISS, there is a strong need for real-time collaboration during task execution.

*Figure 3. ESA Astronaut Thomas Reiter executing a checklist procedure in the US Destiny laboratory (image courtesy: ESA/NASA Image Archives)*

These limitations have not gone unnoticed. Both ESA and NASA are constantly investigating process and technology changes to improve crew task performance and to support collaboration between crew and ground specialists.

In recent years, increased attention has been paid towards wearable systems, which are well-suited for the ISS environment. A simple use case is provided for clarity. The ESA crew work in the Columbus module where a number of payload racks are installed. These racks comprise of instruments and hardware for on-board experiments and assembly, operations and maintenance of these systems require simultaneous payload procedure access and manual tool manipulation. The crew often have to work in difficult-to-access locations on the ISS and laptops are not always available here.

In such scenarios, wearable displays in combination with mobile computers can eliminate the need for cumbersome and bulky laptops and provide critical task-relevant procedural information on-demand to the crew. Wearable systems can dramatically reduce valuable crew time and in combination with interactive technologies such as speech recognition and augmented reality, improve task performance levels on-board spacecraft.

**Wearable Systems for Human Spaceflight**

In recent years, ESA has initiated a number of technology development activities to evaluate wearable procedure support systems. The WEAR++ project (Figure 4b,c,d) demonstrated by Astronaut Frank De Winne in 2009 evaluated a head-mounted system that allowed procedures to be viewed and navigated using speech recognition with information relevant to the procedure overlaid on real-world objects in 3D using augmented reality (De Weerdt et al., 2010). Despite some limitations, due in most part to the unavailability of mobile computers, operational challenges with accurate augmented reality rendering and immature speech recognition technology; the experiment highlighted the benefits of mobile procedure displays in flight operations. More recently, the voice activated procedure viewer (vaPV) system was tested on-board (Figure 4a) to evaluate the benefits of speech recognition as a hands-free input modality for procedure navigation (Wolff, 2013).

Similar concepts have been applied in other space related scenarios, such as medical diagnosis and spacecraft assembly. The Computer Aided Medical Diagnosis and Surgery system (CAMDASS) demonstrated the benefits of head mounted displays and 3D augmented reality guidance in supporting untrained crew with health diagnosis using ultrasound (Nevatia et al., 2011). The Portable Virtual AIT Visualiser (PVAITV) system (Naessens, 2011) demonstrated the benefits of augmented reality and procedure guidance during the assembly of mechanical components in spacecraft cleanrooms.

Although these systems have helped demonstrate the benefits of heads-up procedure support, it has taken some time for the required technology to reach a level deemed feasible for spaceflight.

In recent years, improved optics and display technologies have resulted in a number of light-weight and ergonomic head mounted displays. Simultaneously, the mobile technology market is now flooded with powerful tablets and smartphones with display resolutions higher than conventional desktop monitors. A number of companies such as Vuzix and Google are now manufacturing wearable computing solutions that combine head worn computers with integrated displays, audio and trackers. In comparison with heavy HMDs and bulky computers, these devices can help address technology needs on the ISS and support the development of operational systems to improve crew tasks.


*Figure 4 Clockwise from top-left: a) Astronaut Chris Hadfield testing voice recognition on the CRUISE experiment (credit: ESA/CSA); b) Astronaut Frank De Winne training to use the WEAR system (credit: ESA image archive); c) The WEAR head mounted procedure viewer; 4) WEAR user interface rendering procedures and guidance information using augmented reality*

In an on-going activity titled mobile procedure viewer (mobiPV), the ESA and industry are creating a system that aims at solving these challenges faced by the crew such as just-in-time information access, mobility and collaboration. In the following sections, we introduce the system concept and features, outline additional needs identified by end-users at a recent workshop and highlight the human factors challenges needed to make this system an integrated crew tool in ISS operations.

### The Mobile Procedure Viewer Project (mobiPV)

mobiPV is a system designed to assist the crew-member(s) during task execution on-board the ISS, enhance collaboration between crew members or ground stakeholders and is intended as a permanent crew assistant during operations. Primarily a procedure viewer, it provides the crew with a range of complimentary features aimed at improving efficiency during on-board tasks. Its main features are listed in Table 1.

*Table 1. Key mobiPV user-oriented and system features*

| | ***Feature*** | ***Usage*** |
|---|---|---|
| **Software** | **Procedure Execution** | Access procedures stored in flight databases and rendering of step by step instructions to the crew |
| | **Note-taking** | Create and save task critical text, image and video notes during task execution for post-analysis |
| | **Reference materials** | Access to information needed during tasks such as multi-media, documents and images |
| | **Task Planning** | Access to daily task schedules and plans prepared by ground personnel |
| | **3D Rendering** | Rendering of animated 3D CAD models to support assembly, inspection and maintenance tasks |
| | **Communication** | Peer-to-peer communication including text messaging, audio and video conversations and white-boarding |
| | **Collaborative Procedures** | Shared control of procedures between ground and space, and on-the-fly modification of procedure content |
| **User Interfaces** | **Head-mounted displays** | Heads-up rendering of procedure and advanced 3D content |
| | **Speech Recognition** | Hands-free navigation of graphical user interfaces and data input |
| | **Wearable computers** | Mobile processing units with integrated touchscreens for manual data entry and user interface navigation |
| | **Head-worn cameras** | Support first-person image and video sharing with collaborators for situational awareness and task support |

On-board the ISS, mobiPV allows the crew-member to access procedures that are located in flight databases. Before the start of an activity, it can provide access to the crew-member's daily task plan and critical information that the crew needs to know before the start of the activity, either of which may have been recently updated.

Once a procedure is loaded, the crew-member navigates this procedure either using voice commands or the touchscreen. The current step can appear highlighted or displayed independent of other steps. While on a particular procedure step, the crew-member can take notes or start a voice or video conversation with a ground expert to troubleshoot a problem or ask for support. He can also stream video to the ground from his head-mounted camera to improve remote operator situational awareness, i.e. let the ground-based experts look over the shoulder of the astronaut. Multi-media, documents and 3D content associated with the procedure can be called upon at any time and rendered on either the head mounted or mobile displays. In more complex scenarios where both the crew and ground teams need to execute parts of the same procedure, the system allows shared control of procedures between these teams.

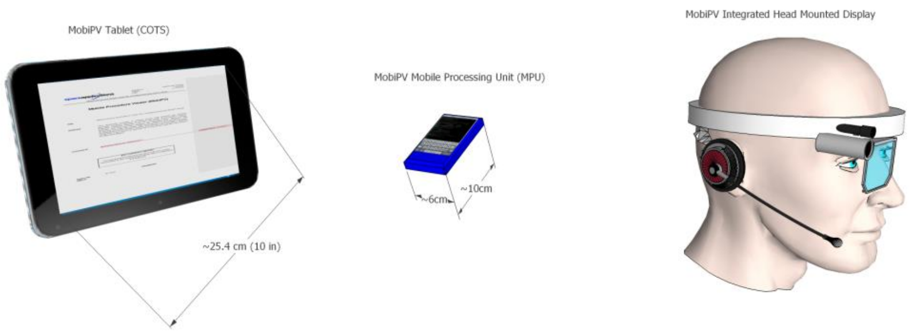


*Figure 5. Initial mobiPV concept with an optical see-through HMD and customized mobile processing unit*

In the initial concept (Figure 5), mobiPV was intended as a customised wearable computer connected to a monocular, optical-see through[3] head mounted display (HMD), an audio headset and a head-worn camera. The HMD is the main display, providing a heads-up view of procedures and procedure content. With augmented reality features in mind, an optical see-through HMD would enable the user to see virtual scenes and the real world seamlessly fused together. A secondary hand-held tablet was also envisioned to provide a large format display for specific content such as documents which are difficult to read on the HMD.

With this concept in mind, in March 2013 the mobiPV engineering team organized a user workshop at the European Astronaut Centre in Cologne to which ISS stakeholders including crew-members (experienced and in-training), flight controllers and training specialists were invited to provide feedback on various aspects of the mobiPV system. Areas of focus were operational scenarios and use cases, hardware and software features and walk-throughs of early graphic user-interface mockups designed for the HMD. Conversations with the end-users led to the discovery of a number of value-adding capabilities and features.

[3] An optical-see through HMD contains optics that allows computer-generated video signals to be overlaid on the visual field seen by the user. In contrast, a video-see through HMD renders computer generated video signals combined with real-world imaging from cameras.

**End-user Feedback**

During the workshop, users were walked through the key features of the system using GUI mockups. Each use case led to many in-depth discussions which are impossible to cover here. For brevity, we will only highlight the key discussions covering system usability and specific value-added capabilities that the end-users asked the design team to include.

**Displays:** The benefit of a monocular HMD as the primary display was recognised by all but a number of concerns were raised. Monocular displays require the user to re-focus one eye on the display and surroundings frequently. Even if the display is off-set from the normal locus of vision, ocular fatigue can occur quickly due to frequent changes in view direction while reading the display.

While a monocular optical-see through HMD is better suited for augmented reality, or where information is required periodically or with minimal display occupation, non see-through heads-up display were seen as more beneficial for reading procedures which are predominantly text or graphic-based. Some end-users even questioned the need for a HMD as a tablet could provide similar or even better display capabilities. To address challenges with the proposed displays, the use of other heads-up displays such as Google Glass in combination with smartphones displays are being investigated along with methods to organise and balance visual information presented to the user on these displays.

**Speech Recognition:** Navigation of the mobiPV graphic user interfaces is expected to be driven primarily by speech. One of the biggest concerns about this technology was the selection of a speech vocabulary that is simple to use while covering all GUI actions. For example, saying “next” provides the following procedure step or “create audio note” allows an audio note to be created. The vocabulary and the speech recognition system must be designed to handle and filter misinterpretations arising from unintentional utterances and background conversations. To avoid such errors, Apple and Google add keywords such as “Siri” or “Glass” to filter unintentional speech recognition. However, frequent repetitions of the same phrases can quickly become frustrating. The vocabulary must be easy to remember and not require user-manuals to use the system and on the ISS, it must be sensitive enough for accurate recognition with 50dBA of background noise which can increase to 70dBA in specific zones. Most importantly, recognition accuracy should be very high to prevent users from rejecting the technology. Hands-free system interaction is a very desirable feature in the ISS environment; designing a speech recognition system to work in the ISS environment however, is one of the biggest challenges in this project.

**Note-taking:** Feedback collected from the crew indicated that they frequently need to create notes, specifically photo and videos of their task environment and share it in real-time with the ground. Additionally, payloads are maintained by various crew-members on different missions and information during these processes needs to be transferred to future missions. For example, a critical parameter change or ad-hoc modification to a system should be available to other system users. Similarly, the same notes should be available to payload operators and instructors to evaluate if systems are functioning nominally or to gather crew feedback and improve future processes and procedures. The current process involves using cameras, transferring data to a hard drive and downloading it to the mission control rooms. This process can take several days. In our design, dynamic note sharing was considered for a future implementation but given its ability to improve task execution, it is now a priority feature.

**Communication:** Features such as text messaging were welcomed by the crew who felt that non-critical information could be exchanged by text instead of occupying the on-board voice system. Peer-to-peer audio-video communication using the mobiPV system was identified as useful for crew-members working on collaborative tasks in different parts of the station however it was clear that peer-to-peer communication between space and ground would be difficult to implement as the current infrastructure did not permit this capability. Whiteboarding was also appreciated particularly by flight controllers and operators who have no effective mechanism to troubleshoot problems remotely.

**3D Rendering:** Given that many on-board procedures involve 3D CAD content (see example in Figure 1), the benefits of this feature was apparent to the crew. The ability to visualize graphic detail on small form displays such as HMDs and smartphones was identified as a challenge. Rendering 3D content using mixed reality techniques was harder to describe without a demonstration of an example system, although it did pique the interest of the audience. Augmented reality was tested previously by one of the astronauts who highlighted the challenges involved in preparing the system for on-board operations (calibration, tracking, etc.).

**Design and Human Factors Challenges**

Designing user-centered systems for human spaceflight such as mobiPV presents a number of unique challenges. References and benchmarks are few and far in-between. Space engineering processes impose a number of safety and security restrictions which means solutions that are taken for granted on the ground need to be tailored to the ISS environment. We list some of the key challenges below.

**User Groups:** In comparison with ground-based studies where user groups are very large, gathering crew feedback early in the design phases is a challenge as crew-members have busy schedules and cannot always dedicate their time to specific activities. Feedback can vary due to mission experiences, socio-technical and cultural backgrounds. For mobiPV, the involvement of crew, both experienced and in-training across the project phases from requirements to design and testing has been made a priority and up until now, four crew-members are actively supporting the design effort.

**Wearable Hardware:** A tablet, smartphone or HMD for use in space will most likely require its hardware to be re-engineered. Internal batteries may need to be replaced by external qualified batteries, which can result in external holders and wiring (therefore electrical hazards). Displays can shatter; a major risk to the crew in the confined ISS environment and these need to be protected and can affect the optical quality of the displays. Hygiene requirements for a single system shared by the crew require a modular design allowing components to be removed, disposed or cleaned. Body worn hardware should not impede dexterity and mobility and safety standards mandate that body-worn displays (auditory, visual or even tactile) must not hinder crew performance. Given the limitations of resupplying the station with upgraded versions, careful thought is needed while considering the physical ergonomics of the system.

**User Interfaces and Interaction:** Due to the scarcity of benchmarks and limited user experience, UI and interaction design are at present exploratory. Assumptions need to be made on user needs and the first versions of the system are expected to remain simple, yet functional. In fact, the crew expects such simple user interfaces as the priorities are time and task performance and not always attractive visual design. Therefore, the UIs navigation and information architecture must be intuitive and easy to learn and most importantly, reliable.

**Design Updates**

Based on the end-user feedback received, the design philosophy of the mobiPV system has been reevaluated. Instead of developing custom solutions and reusing heritage technologies, the design team is now considering the use of off-the-shelf technology such as smartphones and tablets to provide the computing solution for the wearable system. Google's Glass is being considered as a fully integrated mobile computing solution (Figure 6, option 2); however the device is not yet available for consumers. As an alternative, the crew may be provided a wrist worn smartphone as the primary display with a head-mounted camera and audio device (Figure 6, Option 1). During the user evaluations that follow, hardware prototypes and mockups will be used to evaluate and select the best solution preferred by the crew.

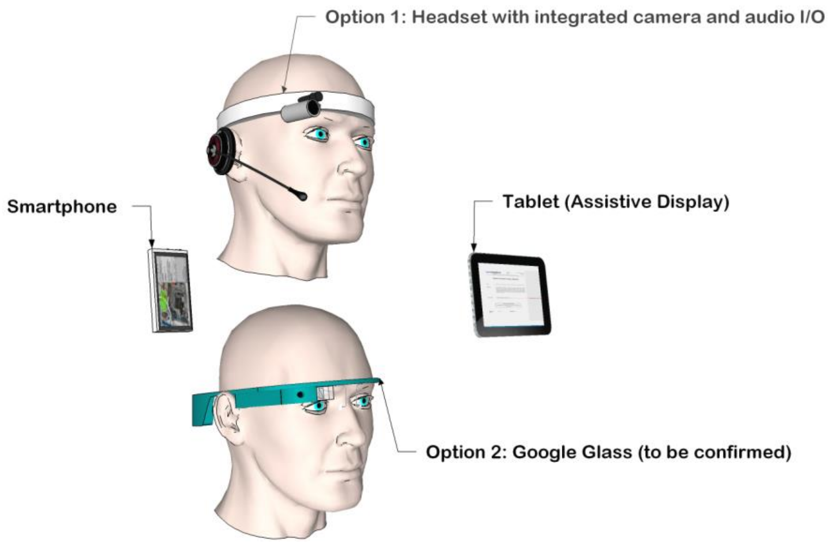


*Figure 6. The updated mobiPV system concept relying on off-the-shelf technology*

## Conclusions

This article, the authors expect, has provided the reader with an overview of the challenges faced by the crew during task execution on spacecraft and the efforts being made by space agencies and industry in developing effective crew support solutions. The mobiPV system is at the time of this writing in its implementation phase and will soon be evaluated by the crew on-board the ISS on a mission planned in late 2015. This valuable opportunity will demonstrate path breaking task support and crew-ground collaboration paradigms and pave the way for mobiPV to be used in future missions as a permanent crew assistant.

## Acknowledgements

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