mobiPV: A New, Wearable Real-Time Collaboration Software for Astronauts Using Mobile Computing Solutions

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mobiPV is an innovative wearable and mobile procedure viewer, which gives astronauts a truly hands-free operations environment and provides them with an instantaneous, direct two-way link with the experts on ground. In turn, the system provides the ground with an exact view of the procedure being executed, including current step marker position, as well as an "astronaut eye view" of the task at hand. All the hardware is Commercial Off the Shelf (COTS) whereby a custom software runs on a smartphone, linked to a wearable head-mounted camera, an audio headset and, optionally, a mobile tablet. Astronauts can navigate through the procedure using either voice commands or the smartphone/tablet touchscreen. A multimedia collaboration environment is available: the crew and ground can exchange audio, text and video notes as well as activate either audio-only or full two-way video communication. All data exchanges are conducted over IP and rely on the Multipurpose Computer and Communication (MPCC) system. mobiPV has been successfully tested during the NEEMO 19 and NEEMO 20 underwater 'aquanaut' missions in 2014 and 2015 as well as during the ESA iriss Mission on the International Space Station (ISS), with the plan to validate increasingly complex experiment utilisation scenarios during future increments on-board the ISS. In general, mobiPV has been shown to improve astronaut efficiency and greatly reduce the time lost suspending an activity to consult laptop/tablet/paper instructions at each step in the procedure. The system also eliminates ground guesswork of what step the crew is currently working on. This paper describes the ISS flight crew operations of this new real-time collaboration software using wearable, mobile computing solutions and its effectiveness in human spaceflight operations.

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I. Introduction

THE ISS program goal of radically increasing crew working time on utilization tasks (i.e. science and technology development) is a challenge to be met on many fronts. For example, performance improvement for crew manual tasks such as system maintenance activities and payload set-up/tear down is required, whilst the anomaly resolution process must also be optimized. A crew informatics response to this efficiency challenge was to create a mobile procedure viewer (mobiPV).

The initial design goals of mobiPV were formulated as:

a) embrace terrestrial mobile and wearable technology so that the required ground support to crew members is always at hand at the work site;
b) improve situational awareness and real-time collaboration between crew and ground expert(s) through a “shared workspace” while operations are in progress.

A. mobiPV Overview

At its core, mobiPV is a procedure viewer enhanced with productivity and collaboration services[i]. In this context, procedures are the standard Operations Data Files (ODF) used on-board the International Space Station for all non-trivial crew activities. mobiPV is compatible with the on-board procedure library containing all validated ODFs applicable to crew activities.

The current mobiPV implementation consists of a flight and a ground segment composed exclusively of Commercial-Off-The-Shelf (COTS) hardware. The application software runs on Linux based OSs (Android on-board and Ubuntu on ground) and is fully customized.

Data links permitting* (i.e. availability of the Ku IP Services (Ku IPS)), mobiPV supports a real-time collaboration environment (a “shared workspace”) for the distributed flight operations team: the astronauts together with their support team on the ground. This collaborative configuration is well suited to contingency operations and has the potential to significantly shorten any anomaly resolution process.

mobiPV provides the following main crew productivity and collaboration services:

1) procedure voice navigation, enabling hands-busy support;
2) real time video streaming of workplace activities (“astronaut eye view”);
3) real-time space-to-ground communications;
4) procedure execution progress synchronization between flight and ground users (i.e. the green step marker is always at the same position on all connected systems);
5) multimedia annotation of procedure steps (text, images, audio and/or video clips).

These services are available, can be initiated on the ground as well as on-board, and the implementation of this application software relies on standard IP network protocols. During real-time operations ground and flight mobiPV systems are connected locally to identical ODF flight libraries thereby avoiding a high bandwidth demand on Ku IPS for loading procedures and synchronizing them as per item 4 above.

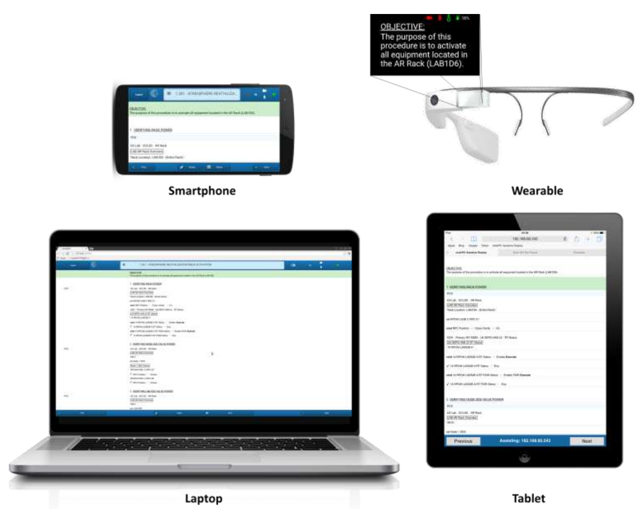

Figure 1. mobiPV devices. *Prime Configuration.*

B. Hardware Configurations

The current implementation involves peer-to-peer connection of one flight system with one ground system. The flight system can be configured in two ways:

a) Prime (Figure 1): the user wears a smartphone on the cuff and complements it with Google Glass for audio, video and auxiliary display functions.

* When Ku IPS is not available, mobiPV can be used in stand-alone mode.

b) Alternate: the smartphone is complemented with a head-worn webcam and a simple mono headset with speaker and microphone.

In both such configurations an iPad can be used as assistive display. As in Figure 2, for example, its larger screen size provides the user with a better operational context (more instructions around the current one are available at a glance) and allows images and video clips to be displayed in larger formats. The Google Glass head mounted display also works as an assistive display however, due to its limited size, it can only render one instruction at any given time.

Notwithstanding the wired connections of the headset and camera in the alternate configuration, all internal mobiPV device communication links are wireless. The external data/video/audio links to/from the smartphone and an ISS wireless base station are also wireless.

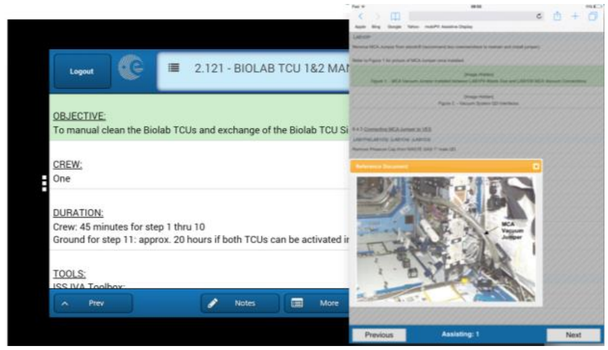

Figure 2. iPad Assistive Display. *Procedure images automatically popup on the assistive tablet, while remaining hidden to save screen space on the smartphone.*

The ground mobiPV is composed of a laptop with a wired webcam and a wireless Bluetooth mono headset. The underlying software architecture allows for additional peripherals (e.g. barcode reader, wireless serial data transfer dongle), as well as a full port to future mainstream COTS mobile devices. In addition the current architecture already allows for a multi-node mobiPV system in operations, where one or many flight systems can be connected with one or many ground systems to support larger team operations efforts.

II. COTS Technology on ISS

There is an increasing trend to use COTS hardware solutions in crew informatics systems for human spaceflight. This approach has pros and cons compared with traditional custom hardware development.

The main advantages are:

a) No development time. Products are market ready and no additional effort needed on hardware development.

b) Physically appealing. Commercial products have a better finish than bespoken solutions. Even though not a technical advantage, this feature has a positive impact on user acceptance.

c) Familiarization. Most crew members use on a daily basis a score of consumer electronic devices such as smartphones, tablets, smart watches, etc. Therefore the familiarization process with a new system that includes them is both easier and faster.

d) Compliance to standards. Commercial products have to fulfil many different norms and standards to be allowed on the market. Products already certified according to such standards can usually go through a faster space qualification process.

e) State of the art technology. In general, custom hardware development takes time and in an era of quick obsolescence of consumer electronics this translates in systems becoming outdated even before their first use.

On the other hand, the adoption of COTS solutions has a few drawbacks:

a) The success and efficiency of the space qualification process heavily depends on support provided by the manufacturer. This is sometimes difficult to obtain when commercial devices currently on the market are involved, as companies tend to keep the details of their designs secret, making it difficult to disclose the information required for the space qualification process, even under NDAs.

b) COTS hardware is normally highly optimized. It is rare to find a modular COTS design to which the application of small customizations is possible. Furthermore, such optimizations, aimed at a specific consumer market, rarely satisfy operational requirements for space applications. This usually has negative impact when modifying it for space in regards to system setup, ergonomics and comfort.

c) Correspondingly, there are no COTS devices for space applications. The device is intended for something else and therefore, has an impact either on the qualification process (removing smartphone radio chips) or in the interfacing process (no serial port on mobile devices).

d) The previous points also extend into the software area. COTS devices, like tablets or phones, come with their own software. Some parts of that software are proprietary and cannot be easily modified. Access to certain features from external applications may be difficult and require significant effort and investigation from the system developers.

C. COTS on ISS

More and more COTS solutions have been adopted in recent years on-board the ISS. ESA, for instance, has been using COTS solutions for some years. In 2009, the WEarable Augmented Reality (WEAR)[ii] technology demonstrator was flown on ISS. This system, like mobiPV was completely based on COTS devices.

Another more modest (hardware-wise) project involving COTS hardware was the CRew User Interface System Enhancement (CRUISE) experiment (2013)[iii]. In this case a COTS headset was qualified to be used in the evaluation of voice commanding technologies onboard.

Beside fully fledged COTS devices (phones, tablets, etc), there is also a trend in industry to exploit emerging technologies as well as low-cost electronics devices. An example of the former is the use of 3D-printed elements. An example of the latter is the AstroPI technological demonstrator currently tested during the Principia mission that makes use of a Raspberry Pi enhanced with different kinds of sensors.

The combination of these technologies appears as an interesting mid-point in the spectrum running from custom hardware development to COTS devices.

D. COTS in mobiPV

The mobiPV project involved COTS devices since the very early stages of development. The main goal of the project is to improve mobility and explore the possibilities inherent to wearable technologies, therefore, the selection of a mobile phone was the logical choice.

Specifically, a Nexus 5 was selected because, of all the devices available, it was the only one of its type with some vendor support to customize the software. Moreover, the manufacturer's offices in Europe also helped to qualify the rechargeable Li-Ion battery and remove the radio amplifiers to avoid interference from cell-network bands. The Nexus 5 is the central element of mobiPV and it proved to be an important asset for the project. However, it is interesting to note that, as mentioned above, it was not possible to strictly use it "Off The Shelf".

Another major mobiPV component is Google Glass. At the beginning, the device was deemed promising because of its small size and simple setup. Its qualification, however, proved difficult, and the drawbacks of the final result outweighed the main advantages of the device. In this case, in fact, it was not possible to obtain manufacturer support for battery qualification. The workaround was to modify the device by removing the original battery and use instead an existing space qualified re-chargeable battery, provided by NASA. This modification was possible thanks to the efforts of ESTEC engineering personnel.

The use of 3D printing technology proved to be necessary for both devices. In the case of the smartphone, a wrist attachment was 3D printed in order to support the original concept of a cuff worn device. For Google Glass it was necessary to 3D print a cover for the display prism such that, if it were to shatter during transportation, any piece of glass would be contained within. In fact, the cover made the display prism compliant with COLUMBUS/ISS safety requirements.

The rest of the mobiPV components (head mounted camera, headset, cabling, chargers) didn't pose any major issue and could be used as-is.

E. Interfacing with Current ISS Technology

mobiPV interfaces with two main ISS systems: the on-board wireless network and the MPCC. The former provides connectivity to a number of different services, for instance the IPV server containing all the on-board procedures. The latter is still under development but, in principle, it is intended to enable point to point TCP/IP connectivity between ground and flight segments and enable the so-called Class III payload operations. (A Class III payload can conceptually be operated by its user from any place where an internet connection supported by Ku IPS and MPCC services are available). mobiPV does not fully fit the definition of a Class III payload due to its bidirectional real-time audio/video capability and therefore, interfacing with the MPCC system was a challenge especially for some system functionalities.

III. Underwater Operational Verification

The success of any hardware/software solution is largely determined by how much user feedback is collected during development and how well this is incorporated in the final product. Such feedback is essential to tweak the user interface, improve performance, find and eliminate bugs, as well as identify which features are worthwhile and which are better left out. This is especially important with a system providing enhanced real-time collaboration in the complex technical and operational environment of the International Space Station.

Awareness of this fundamental principle has characterized mobiPV since its inception. Already in the very early development stages, informal user evaluation sessions were conducted at the European Astronaut Centre in Cologne to collect feedback from astronauts as well as ground support personnel. As the system matured and grew increasingly more complex, those user evaluations were formalized and became important project milestones. The typical evaluation scenario involved the execution, with the aid of mobiPV, of a real flight procedure focused on hands-busy, complex operations where astronauts would benefit the most from a wearable system and a closer collaboration with the "ground".

Those evaluations provided frequent, valuable feedback but lacked a few fundamental elements: the activities were executed in "stand-alone" laboratory conditions rather than in the framework of a tight activity plan and in a realistic, space-like operational environment.

In order to fill this gap, at least partially, two special user evaluations were run by astronauts and flight controllers inside Aquarius, an underwater habitat twenty miles off the coast of Florida, in the framework of the NASA Extreme Environment Mission Operations (NEEMO) program. A first test was conducted in summer 2014 during NEEMO 19, followed a year later by a second one during NEEMO 20.

The relevance of those tests cannot be overstated. NEEMO provides what is probably the closest space-like operational environment not involving rocket propulsion. Aquanauts are confined for one to two weeks in a pressurized habitat 20m (65ft) under the surface of the sea. They have a busy schedule and are supported in real-time by a Mission Control Centre. Schedule pressure, isolation, limited communication infrastructure, as well as a real component of risk combine in a unique mix that has been exploited over the years to test a number of precursor technologies.

Figure 3. NEEMO 19 Aquarius underwater habitat. *Mogensen using mobiPV prime configuration to perform Skin-B, a procedure currently used on the ISS (ESA).*

F. NEEMO 19

In NEEMO 19 a mobiPV prototype was put through its paces by ESA astronaut Andreas Mogensen (who later checked-out the final system in space during the iriss mission) and ESA instructor Herve Stevenin.

In this test, the prime system configuration was used. The smartphone was as usual the centrepiece of the system, with Google Glass covering the function of head mounted camera, assistive display and headset, and the iPad providing an additional assistive display with large screen real-estate. The activity executed with mobiPV as can be seen in Figure 3 was Skin-B, a real scientific protocol normally performed by astronauts in space.

The test involved the verification of all mobiPV main features: step marker synchronisation, multimedia note exchange and real-time audio/video interaction with a ground operator located at the

NEEMO Mission Control Centre. The overall results of NEEMO 19 were encouraging. mobiPV clearly showed the potential for enhanced space-to-ground collaboration: a tighter integration between the efforts of crew and mission control resulting in a more efficient use of crew time. The test was also useful to identify areas of improvement: voice commanding, Google Glass limited battery life, as well as the need for a networking protocol that would better cope with limited bandwidth and frequent outages.

G. NEEMO 20

ESA astronaut Luca Parmitano, together with NASA astronauts Serena Aunon and Dave Coan (Figure 4) as well as JAXA astronaut Norishige Kanai evaluated in the summer of 2015 an updated version of mobiPV during NEEMO 20. This time the alternate configuration was chosen: the smartphone was complemented by a head mounted camera, a wired headset and an iPad. The activity executed was again Skin-B, thus allowing more meaningful comparisons with NEEMO 19.

Figure 4. NEEMO 20 Aquarius. *Coan wearing mobiPV in the alternate configuration for Skin-B (NASA).*

Apart from an updated software, the main novelty of NEEMO 20 was the verification of a simulated multi-centre collaboration setup. The aquanauts did not rely any longer just on mission control, but could also interface with Skin-B activity experts located at the European Astronaut Centre in Cologne as shown in Figure 5.

Once more the evaluation results were encouraging: the system was definitely more mature than in NEEMO 19 and could better cope with the difficult network environment of Aquarius. Moreover, the simulated multi-centre setup proved to be a valuable addition. On the other hand, problems still persisted with the voice recognition and the cables connecting the various hardware turned out to be quite cumbersome.

Figure 5. Live multi-centre operations. *Kanai underwater in Aquarius works simultaneously with CAPCOM Stevenin in Florida, USA and Skin-B payload specialists in Cologne, Germany (ESA).*

IV. Spaceflight Operational Verification

The initial activities on the ISS aimed to systematically test each of the mobiPV features for both configurations. The tests were slated for Andreas Mogensen during his 10day mission in September 2015[iv].

H. International Space Station

On the International Space Station, the crew work to very tight schedules. In this environment mobiPV was envisioned to be extremely useful to save crew time, increase accuracy and make it easier for crew to take on any task while keeping both hands free. A key feature for ground controllers is the ability to know exactly where crew is in the procedure thus eliminating the current guesswork, which is anyway only possible when cabin video or telemetry from the equipment being operated is available.

mobiPV enables new ways of interaction, including a direct connection between the crew member on board and the activity experts on ground. The idea is to complement the current approach where the Flight Control Team "owns" all S/G communications and acts as intermediary between the astronauts and the principle investigators or payload developers on ground. In order to make this direct interaction possible whilst still keeping the Flight Control Team aware of what is happening, redistribution of the mobiPV internal video/audio channels is necessary. Those channels are carried as IP traffic through the MPCC and then further redistributed on ground to feed them into the standard ISS distribution system and make it available to the various control centres.

As mentioned, mobiPV was designed to enable multi-party collaboration models and therefore, enabling the different parties involved in an activity to have their own mobiPV unit with the ability to monitor and interactively join the on-going session. This whole concept, when fully deployed, will enable a more integrated solution for the whole mission team situational awareness.

Since Andreas Mogensen's Soyuz had to adopt a longer rendezvous (Two days instead of six hours) and docking profile, the original ten day docked mission was replanned into eight days and, as a result, the time allocated to mobiPV was greatly reduced. In sight of this reduction it was decided to test only the alternate configuration.

The smartphones were both fully charged a day prior in order to have a prime and backup phone in case one was required. Both phones are identical such that crew could chose to use either and quickly switch from one to the other in case of need.

On the day of execution, the phone fit snugly into the 3D printed cuff worn mount. It took, however, some manoeuvring to set up the cables, as we had anticipated and Mogensen had trained for, and link the peripherals to the smartphone. He connected the wired audio headset to the audio adapter cable jacks and inserted the adapter cable to the smartphone. The head mounted webcam was connected via USB to the smartphone and all the cabling was secured with a velcro strap to the crew arm to keep it out of the way.

Afterwards, Mogensen activated the smartphone, verified battery levels were above 80%, connected to the appropriate network on the Node 2 Wireless Access Point, and started the mobiPV software. The ODF library loaded automatically and the full mobiPV connection to ground worked flawlessly at the first attempt. He then powered up the iPad and navigated on the Safari browser to the IP address that would link it automatically to the mobiPV software on the smartphone.

Mogensen set the smartphone as master, disabled the speech recognition for the first part of the test and loaded a designated procedure as per the test sequence. On the ground terminal everything operated nominally: our system instantly recognized the master instance, configured itself as slave and mirrored the newly opened procedure on our laptop screen at EAC, which was screencast to Col-CC in real time (Figure 6). Mogensen pressed next and previous on the onscreen display to scroll forward and backward through the procedure and the ground terminal synchronized the green step marker as expected. Crew also verified that the iPad synchronized.

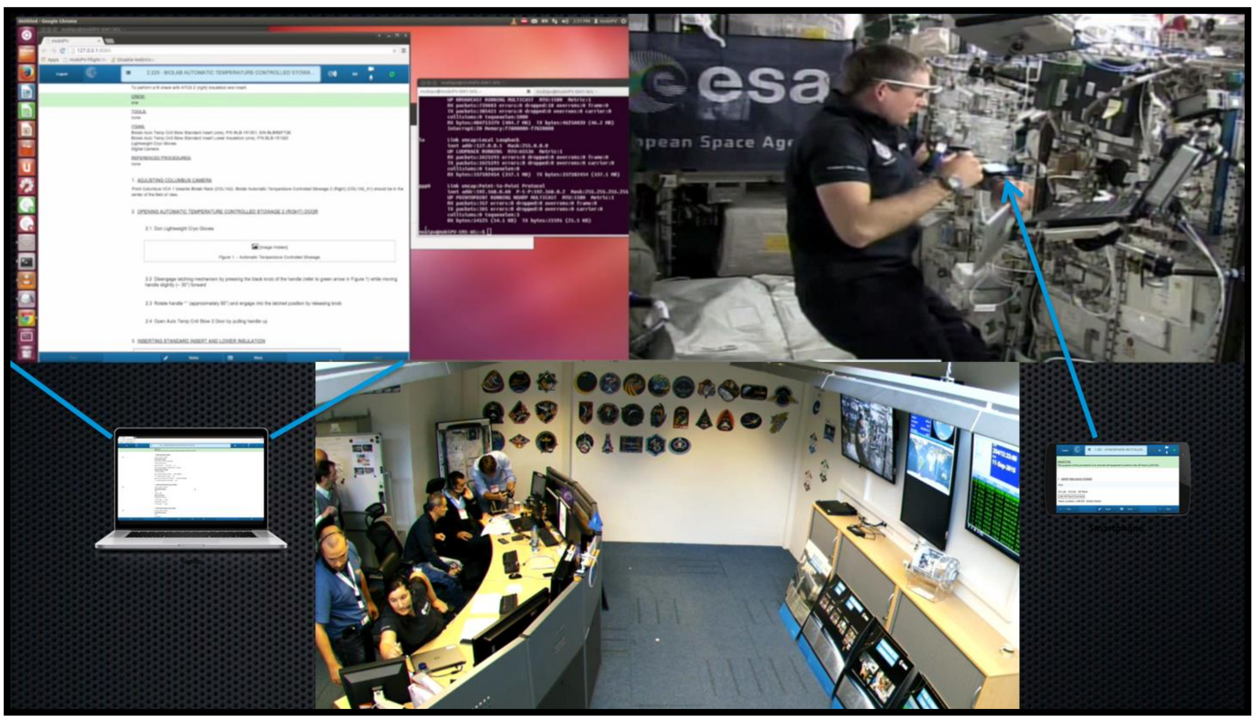

Figure 6. Live space to ground mobiPV operations. *Ground terminal and ISS devices synchronized (ESA).*

Mogensen then enabled the speech recognition and tested the voice commanding. This test unfortunately failed due to issues with the wired audio headset that was handed down from a previous ISS experiment. The ground quickly instructed the crew to move on and speech recognition was disabled once more. The cause of the headset failure was traced back to the strict order that must be followed while connecting peripherals to the smartphone.

Crew and ground sent successful text notes and image notes (Figure 7) and video notes back and forth. Of course, because of the abovementioned audio issue, the crew video note was without audio and we had to skip the recording of audio notes on the crew device. A real time two-way video link was also established between space and ground and crew were able to view the flight controllers and vice versa with fairly good quality.

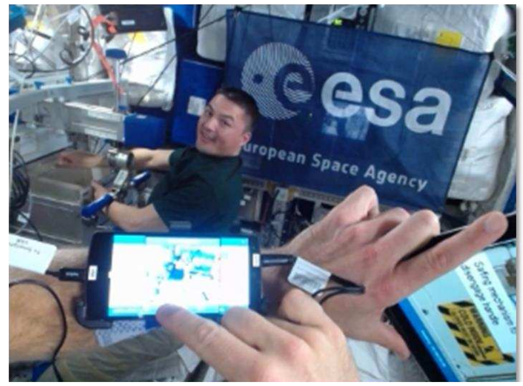

Figure 7. Image note. *"Astronaut Eye View" from the head-worn webcam (ESA).*

The first test concluded at this point as planned and the crew reconfigured the iPad back to nominal station configuration while the ground downloaded the log files and disengaged the video link.

Bearing in mind that the flight segment consisted of a new device, connected to the onboard wifi, routed to the ground via the TDRS satellites and that the ground segment consisted of the initial receiving dish in Whitesands, POIC in Huntsville, the MCC at Houston, the Col-CC in Munich and finally the ground terminal at EAC in Cologne, with return links, this was very impressive.

A second mobiPV test is planned for 2016 to check out the prime configuration using Google Glass.

V. Results

I. Comparison of NEEMO 19 and 20 Operations

The software versions had developed considerably between NEEMO 19 and 20. NEEMO crew members had a direct network connection and found the collaborative tool between aquanauts and CAPCOM to be useful with a smooth continuous video both ways. Crew gave feedback in NEEMO 19 which was incorporated into the NEEMO 20 version. This was well received, improving the network and testing out the multi user communication system.

The mobiPV versions utilized in NEEMO 19 and NEEMO 20 were different development sequences and the next generation to be used in NEEMO 21 follows on from the NEEMO 19 model, while the ISS model is an exact copy of the mobiPV hardware and software used in NEEMO 20.

J. Comparison of NEEMO and ISS Operations

NEEMO and ISS operations have the obvious difference of microgravity during operations which changes the cable management approach. The communications network in NEEMO is much more straightforward than space to ground so the video and high bandwidth connections are more fluid and easier to manage. Safety constraints meant removing internal batteries from the Google Glass which introduced a large NASA approved external battery with two connection cables, an activity to charge this and the need for a belt to mount it during use. In NEEMO this is simply a wireless operation and wearable unit.

K. Crew Feedback

NEEMO 19 was extremely useful for Andreas Mogensen as he was able to extensively use mobiPV prior to his ISS mission. This experience combined with two hardware inclusive simulations and training at EAC prepared him very well for the on-board usage.

Crew has stated that they would like more wireless technology, for example to substitute the wired earpiece with a wireless Bluetooth earpiece and to find a non-cabled solution to the ISS requirements of the large external battery, a downside of having to modify a non-space qualified COTS device.

Overall ISS crew gave the feedback that they were very well supported by ground teams and the training was excellent, particularly as they used mobiPV twice, also during NEEMO 19.

Crew would like to see the mobiPV smartphone as a crew preference device that they can pick up in standalone mode at anytime and use instead of a laptop or the iPad for any activity. In principle, this is already possible with the hardware and software available on-board.

L. Flight Controller Feedback

The ability to see exactly which step the crew was working on, synchronized in real time, was highly appreciated by flight controllers. The two-way video was not found to be useful in the first operational test due to occasional unpredictable network performance with regard to bandwidth. All the messaging features worked extremely well.

VI. Conclusion

The first version of mobiPV was tested on NEEMO 19 in 2014, a different version was utilized on NEEMO 20 in 2015 followed in the same year by that identical version being demonstrated in space on the ISS. The final on-board demonstration is scheduled in early 2017. All in all mobiPV has been used by ESA astronaut Luca Parmitano, NASA astronauts Serena Aunon and Dave Coan, JAXA astronaut Norishige Kanai, ESA astronaut Andreas Mogensen and ESA astronaut Timothy Peake spanning NEEMO 19 to ISS Increment 47. NASA astronaut Kate Rubins and JAXA astronaut Takuya Onishi have been trained for Increment 48. Crew have expressed a strong interest in future development and integration of the mobile procedure viewer into crew operations onboard the International Space Station.

mobiPV has been shown to improve astronaut efficiency and greatly reduce the time lost suspending an activity to consult laptop/tablet/paper instructions at each step in the procedure. The system also eliminates ground guesswork of what step the crew is currently working on.

The advantages of using COTS devices has resulted in simplifying the qualification of mobiPV for a more agile technology deployment, proving to be both cost effective and functional. Increasing TRL levels of other COTS hardware would lead to wider options and even better performance for future hardware configurations.

In July 2016 the second generation of mobiPV from NEEMO 19 will be field tested underwater by the NEEMO 21 crew.

Future everyday utilization of mobiPV includes making the phone available as a standalone tool so that it can potentially be picked up anytime as a crew preference, in the same way the iPad is currently utilized, as an alternative to a fixed laptop to view procedures. The next generation of mobiPV might include a barcode reader for faster stowage operations as well as a multi-collaboration tool so that more complex scenarios can be planned on the ISS: it can be used by multiple astronauts at the same time as well as multi-user ground terminals for the flight controllers and payload specialist to interact directly, efficiently and effectively with the crew optimizing systems and payload utilization time.

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