Toward the First Force-Reflection Experiment on the International Space Station

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Abstract

This paper introduces the Haptics-1 ISS Payload and experiment, which has been developed by ESA's Telerobotics & Haptics Laboratory. Haptics-1 allows conducting a first extensive set of human factor measurements and measurements of variability of human motor-control capabilities of the upper extremity during extended exposure to microgravity. Haptics-1 consists of a high resolution force reflective Joystick with a single degree of freedom (a force manipulandum), a touch-screen tablet PC with the experiment interface software and all required periphery to conduct multiple experiment protocols with crew-in-the-loop. Haptics-1 has a flexible software framework allowing software up-load and experiment parameter changes from ground. Moreover, Haptics-1 followed an agile development process, which allowed developing the experiment in less than 16 months from scratch, up to delivery to ATV-5 for launch to ISS in summer 2014.

1 Introduction

In future spaceflight and exploration scenarios, humans will be executing tasks remotely with advanced robotic devices. Such robotic devices can be located on the surface of a planet or other celestial body, while humans can perform teleoperation with such robots from a safe and economically viable distance such as from orbit of the celestial body. This approach allows cost savings, increases exploration scenario feasibility and can still significantly enhance the quality of surface operations that can be performed w.r.t. pure robotic probes or w.r.t. short human presence. This is why ESA and NASA have recently started a series of projects aimed at better understanding the requirements for such combined human-robotic orbit-to-ground mission scenarios [1-3].

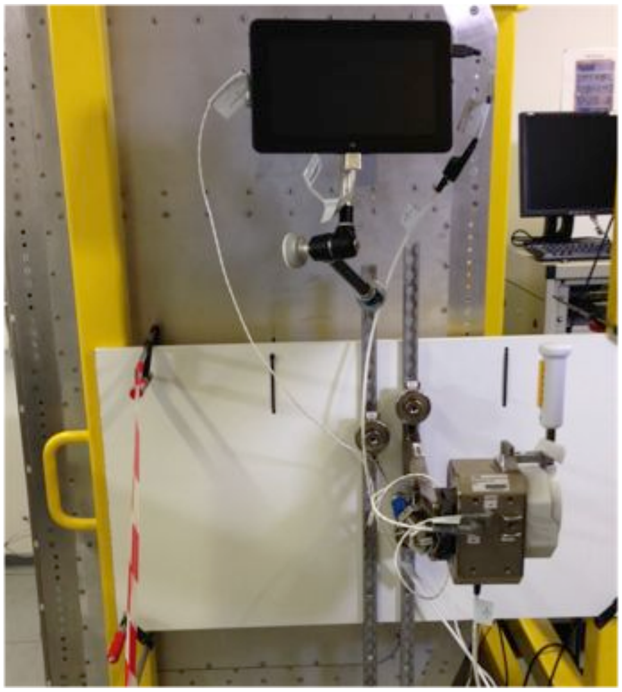

Fig. 1: The Haptics-1 Flight-spare model as set-up for crew training at the European Astronaut Centre in Germany. The system consists of the 1DOF Setup (Joystick), the touch-screen Tablet PC on a bogen arm and all periphery. Here set-up in wall-mount configuration.

Moreover, technical joint developments have been started on international scale, to address the important aspects of robot system interoperability [4] [5]. ESA has shown strong competence in the field of real-time teleoperation with force feedback [6] and will perform related technology demonstration experiments on-board the International Space Station in the coming months and years. The Haptics-1 experiment is the first of this sequence of experiments and aims at providing a first fundamental data-set helpful for the design of haptic devices for use inside micro-gravity environments.

It is the goal of this paper to provide the rationale for the Haptics-1 experiment, to outline the experiment hardware and software components and to give a brief overview of the employed agile development process for ISS payload development.

2 Challenges of teleoperation from space

Before being able to develop high performance haptic teleoperation systems for usage by astronaut crew from space, a number of technical and fundamental challenges need to be solved. The engineering challenges related with bilateral control scenarios from space to ground are related to:

- Understanding how to enable stable and transparent bilateral control between master (in microgravity) and slave devices (on ground) via communication links with non-ideal transmission characteristics and potentially significant delay;
- Understanding of how to enable good situational awareness of the operators during remote operations through video, overlay or other feedback mechanisms;
- Finding an appropriate mechatronics design concept that is sufficiently lightweight, high performance, compact, safe, robust and with sufficiently low power consumption when used on-board a space station;
- Having knowledge about the design of a system that is sufficiently simple and robust to be used for bilateral control by non robotic experts;
- Having no a-priori knowledge of an existing proof-of-concept system that allows intuitive and safe operations under uncertainties in the communications channel and environment;

The scientific challenge that needs to be solved to be able to design advanced haptic human-machine interfaces for usage in space is the following:

- No human factors data currently exists, that is related to haptic and human movement control and perception changes in microgravity (i.e. does human perception e.g. of the upper extremity, improve or degrade? What are the thresholds? What magnitudes of feedback forces are necessary?)

It was for answering those questions that Haptics-1 has been implemented as a first pre-cursor experiment on ISS, before embarking on the development of a more complete robotic control workstation for bilateral control to teleoperate more advanced robotic systems with more degrees of freedom.

3 Goal of Haptics-1

It is the goal of the Haptics-1 experiment, to collect data from 3-5 ISS crew during an extensive human-in-the-loop experiment, in order to (a) define human physiological and proprioceptive changes in micro-gravity related to force and motion perception and control, to (b) validate the suitability of exclusively "crew-guided procedures" (i.e. without PODF procedures for the actual experiment conduct) implemented on an experiment specific touch-screen PC, to (c) validate the mechatronic hardware and safety concept of a single-degree-of-freedom haptic Joystick, to (d) experiment with the establishing of a new agile development process for ISS payloads, and to define (e) which fixation of crew to a haptic control device bears the more optimal performance during teleoperation like remote control tasks (wall-mount joystick or body-mount joystick).

4 Haptics-1 Components

All sub-systems of the Haptics-1 hardware are shown on Figure 1. It consists of the single degree of freedom mechatronic joystick (1DOF Setup), a modified Dell Latitude 10 tablet with touch-screen (Tablet PC), the Seat Track I/F Assembly to connect and tighten the 1DOF Setup to the seat tracks mounted on the racks of the ISS Columbus module, a Bogen-arm and all cabling necessary to power the system and to exchange data via a LAN network between the Tablet PC and the 1DOF Setup. The sole interface to ISS is the mechanical one towards the seat tracks (deck rack chosen) and an electrical 28V interface to the portable power supply (PPS).

Fig. 2: Haptics-1 FM as packed in flight pouch

Figure 2 shows the Haptics-1 hardware when packed into its fireproof Nomex covered pyrell/minicel flight container for launch on the Automated Transfer Vehicle ATV-5.

4.1 The 1-DOF Setup

The 1-DOF Setup is a fully integrated haptic high performance Joystick that contains a RoboDrive ILM50x14 brushless DC motor, an EtherCAT based motor controller (ELMO Gold Solo Hornet), an embedded computer (CompuLab), a custom designed joint output torque sensor with overload protection as well as all necessary power supply and conditioning electronics for the 1-DOF setup's internal sub-systems as well as for the connected Tablet PC. Following picture shows the 1-DOF Setup in detail with it's main power switch, primary power supply and secondary power supply output towards the Tablet PC. The Joystick is locked in place by a locking mechanism that can be easily removed by hand. This mechanism is used to clamp the joint to perform a torque sensor automatic identification.

Fig. 3: Haptics-1 1DOF Setup (Joystick) including a brushless DC actuator, torque sensor and full embedded real-time computing.

The 1DOF Setup housing consists of a solid aluminium casing that integrates structurally most of the electronic components. The aluminium casings are nickel-plated in order to ensure good conductivity. The structure of the system is used as ground and the grounding concept employed for all of the Haptics-1 system is Distributed-Single-Point Ground, which is good for low-to-high frequency disturbance rejection.

The 1DOF Setup output consists of a handle-bar with a safety switch (Fig. 3, yellow), which enables or cuts the power supply to the brushless RoboDrive motor. The motor shaft is connected via a Capstan reducer to the joint output torque sensor. All output mechanics of the 1DOF are covered in FDM molded polycarbonate cover plates with an internal silver coating for good EMC/EMI compatibility. The output torque sensor is over load protected. The 1DOF System can generate an output torque larger than 13 Nm and a torque resolution of 40 mNm can be measured on the output torque sensor. The sensor acquisition and the motor control is performed via an high-speed EtherCAT bus. The entire experiment control software runs on the embedded computer (Intel Atom Z530 1.6 GHz) with control cycle rates as high as 4kHz. The thermal design of the 1DOFsetup is a passive one.

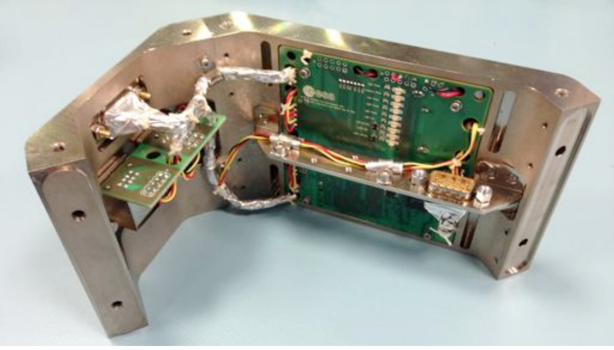

Fig. 4: Flight integrated computer board and periphery in the side-walls of the 1DOF setup housing. Cable harness integrated in flight quality.

4.2 The Touch Screen Tablet PC

Following an extensive search for a suitable Tablet PC for usage on ISS, a Dell Latitude 10 model has been chosen. In order to qualify it for flight, a screen protection was applied, the primary lithium polymer battery was removed and the Tablet was tested for vacuum, offgassing and mechanical loads compatibility.

A fracture test performed on the Gorilla Glass^{TM} screen revealed that with a three-fold repetition of kick-load test (1.15 kN applied on a steel-pin with surface area of 12.7 mm^2) did not result in a screen fracture. A fourth repetition with 556 N applied on a steel pin with only 1.5 mm^2 contact area (inadvertent tool impact) finally cracked the screen. Following the cracking and inspection, no particles had been released. Following pictures show the application of the screen protection with a protective foil and ScotchWeld 2216 before and during the screen impact test campaign.

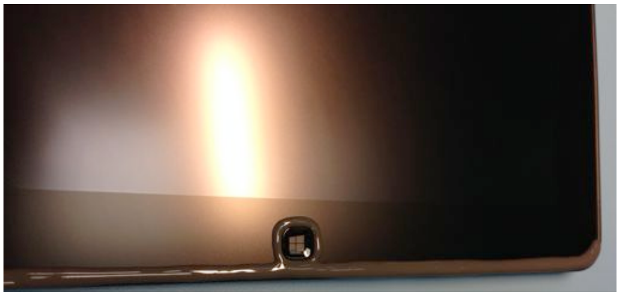

Fig. 5: Detail of application of screen protective foil to the Dell Latitude 10 tablet for flight qualification.

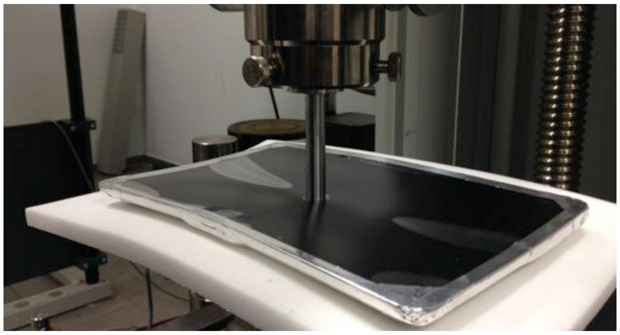

Fig. 6: Dell Latitude 10 Tablet PC surviving a 1.15 kN screen fracture test.

4.3 Wall-mount and Body-mount attachment

In order to attach the 1DOF Setup (Joystick) to either a wall-mount configuration or to a body-mount configuration an interface mechanism has been designed and implemented. The Seat-track interface assembly allows to attach the 1DOF setup to any pair of adjacent seat track strips. The 1DOF setup then attaches to a photographic adapter plate. In order to perform the experiments also in a body-mounted configuration, a user vest has been developed that also accommodates two adjacent pairs of seat-tracks in the front for attaching the joystick.

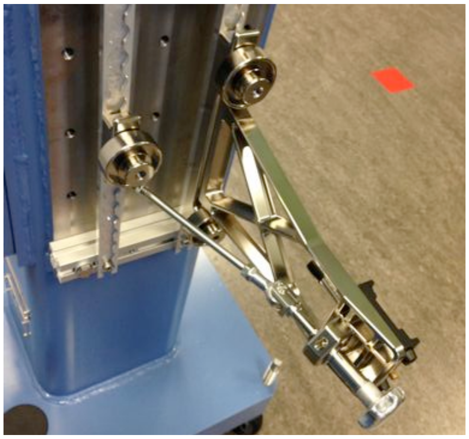

Fig. 7: Seat track interface assembly to tighten the Joystick in a backlash-free manner to adjacent seat track strips.

Following figure depicts the body-vest of the Haptics-1 system, which can also accommodate the bogen-arm, to which the Tablet PC is attached.

Fig. 8: Body-vest of the Haptics-1 system for experimentation in a body-grounded setup.

5 Experiment Interface for Crew

The sole interface for crew during actual experiment conduct is the software App running on the touch screen Tablet. The Haptics-1 GUI is designed to automatically guide crew through the entire experiment conduct. Moreover, the Haptics-1 GUI manages the user input required by the experiments, the logging of all data including the naming of output log files and also allows to select the experiment conditions (wall-mount versus body-mount). Figure 9 illustrates the main experiments screen on the Haptics-1 GUI App. Crew can select which protocol to perform and icons relate in a simple fashion to the scopes of the experiments. Each experiment then opens a dedicated experiment menu, which guides the operator through the correct conduct.

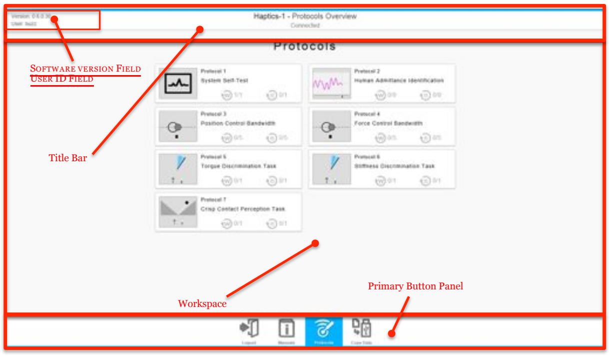

Fig. 9: Experiment screen of the Haptics-1 GUI App to select the various experiments (protocols) that can be performed by crew.

6 Software Implementation

All control software (i.e. motor control, experiment state control) of the experiment is deployed on a real-time Linux on the Intel Atom PC within the 1DOF setup. This software controls all inputs and outputs from/to the motor, the torque sensor and the joint output encoders. All safety critical features are implemented in hardware, such as power management through safety switches and joint end-stop switches.

The real-time control software on the 1DOF system communicates with the Haptics-1 GUI App, in order to integrate the conduct of all protocols in a seamless fashion. Communication between the GUI on the Tablet PC and the Joystick is implemented using Data Distribution Services (RTI DDS).

The real-time control software is implemented in C/C++ and the GUI App is implemented using web-technologies such as html and javascript.

7 Haptics-1 Protocols

All Haptics-1 protocols will be performed on ground (Baseline Data Collection) and in space. Moreover, all of the seven protocols will be performed in two different mounting configurations. Once the 1DOF joystick will be externally grounded, like a normal desk-top joystick as we know it (wall-mount condition). Once the 1DOF joystick will be grounded on the operator body through the user-vest with the seat track strips. This simulates a wearable haptic device (body-mount condition). Following figure illustrates the experiment setup for the body-mount sessions.

Fig. 10: Body-mount configuration test with the Haptics-1 engineering model.

7.1 System Self Test

During the system self test, a full identification of the mechatronic behavior and performance of the 1DOF setup is performed. The self test is first performed in 'locked' position, with the output handle-bar clamped (current input to torque output identification) and then with the output handle-bar loose (current input to position output identification). These two identifications are used to calibrate the sensors, to check the correct functioning of the joint impedance and joint position controllers and allow to verify the dynamic properties of the 1DOF system when exposed to microgravity.

7.2 Human Impedance Identification

The second protocol aims at identifying the admittance of the upper extremity under a variety of voluntarily applied neuromuscular control tunings, being (relax, pursuit and compensate). This protocol will allow analyzing the changes of human neuromuscular control activity and performance between ground (1-G) and microgravity, since it is currently not understood how the environment affects such parameters.

7.3 Position / Force Control Bandwidth Tasks

In the third protocol, users are tasked to track a multisine input signal on the Tablet PC screen by performing a motion on the 1DOF setup Joystick. The target signal is random and has a varying frequency content. The bandwidth of maximum human voluntary upper extremity movement will be identified in a large frequency spectrum that covers the range of velocities that a human hand can exert in free motion.

For the fourth protocol, crew has to track a target signal by performing a pure force input to the then static (in position control) 1DOF setup joystick. This protocol measures the maximum voluntarily controllable force of the human arm on ground and in micro-gravity.

7.4 Force / Stiffness Discrimination Tasks

In order to get a first set of design data related to difference thresholds in space, the fifth and sixth protocols will perform JND (just noticeable difference) tests.

The fifth protocol presents a series of 200 force stimuli on the crew's hand and the Haptics-1 GUI then requests to rate the more profound stimulus. In the sixth protocol, stiffness stimuli are presented and the crew needs to probe two stiffness pairs and then rate the stiffer one on the GUI App.

7.5 Crisp Contact Detection Task

In this seventh protocol, engineering parameters are optimized, based on a similar test than for the above JND tests. Here, multiple parameters of a simulated 'crisp' contact are varied, in order to determine which maximum torque, stiffness and damping (i.e. contact model parameters) parameters are still distinguishable from within microgravity for the various mounting configurations. This test will provide insight in the required performances for a more extensive haptic device for usage in a space environment.

8 The Haptics-1 development process

The Haptics-1 development followed the full system engineering processes to ensure payload safety, operational safety, medical acceptance and full transparency of the development process required for safety relevant quality assurance. All Haptics-1 hardware was assembled and integrated by experts certified to perform flight integration of payloads for ISS.

This means that commercial of the shelf components have been used as much as possible, while at the same time doing modifications and tests to ensure safe operation by astronaut crew. It turned out that reliability is likely higher for COTS units than for custom designed parts and components, which is why this was deemed a less important aspect in the development.

Moreover, the documentation process for Haptics-1 has been streamlined to those documents as needed for acceptance by the appropriate flight certification bodies. As such, full documentation was produced for flight safety, medical approval, research ethics, operational products, flight acceptance data and all records necessary to demonstrate acceptable product assurance related to safety aspects. Formal project management documentation has been reduced to a system engineering management plan and to a lab. Internal monitoring and requirements tracking system. Further management documentation has been created only within the project team, making use of appropriate engineering tools.

All mechanical and electrical designs and all Haptics-1 software has been developed under strict configuration control and design information was only released to third parties once the design was sufficiently mature in CDR stage. This avoided lengthy review loops and helped to cut the development time in the beginning of the project significiantly, without loosing quality or focus on the project. Requirements tracing has been performed from the start of the process to the end, within the project team. A small and agile development team that was fully co-located supported this agile approach. In this way, the entire Haptics-1 payload was developed in the time-frame from December 2012 until March 2014.

9 Conclusions

The Haptics-1 payload has been developed entirely within the ESA/ESTEC engineering laboratories. A fast development cycle has been employed which allowed developing the payload from scratch within only 16 months. The Haptics-1 payload has passed successful flight acceptance review in May 2014 and has been delivered for launch to ISS with the ATV-5 in summer 2014. First experiments with ESA astronauts on-board the International Space Station are expected to take place in increments 40/41.

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